



IRRIGATION WATER USE IN THE DANUBE BASIN: FACTS, GOVERNANCE AND APPROACH TO SUSTAINABILITY

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Abstract

In this paper we assess the irrigation water use in the Danube Basin, highlight its complexity, identify future challenges and show the relevance for a basin-wide integrative irrigation management plan as part of a more holistic and coherent resource policy. In this sense, we base our integrative regional assessments of the water-food-energy nexus on insights from an extensive review and scientific synthesis of the Danube Basin and region, experimental field studies on irrigation and agricultural water consumption, current irrigation related policies and strategies in most of the Danube countries, and regulatory frameworks on resources at European Union level. We show that a basin-wide integrative approach to water use calls for the evaluation of resource use trade-offs, resonates with the need for transdisciplinary research in addressing nexus challenges and supports integrative resource management policies within which irrigation water use represents an inherent part. In this respect, we propose a transdisciplinary research framework on sustainable irrigation water use in the Danube Basin. The findings were summarized into four interconnected problem areas in the Danube Basin, which directly or indirectly relate to irrigation strategies and resource policies: prospective water scarcity and Danube water connectedness, agricultural droughts, present and future level of potential yields, and science based proactive decision-making.

Keywords: basin-wide irrigation management, resource policies, transdisciplinary research, Danube Basin

INTRODUCTION

Irrigation is by far the largest user of blue water regionally and worldwide (Foley et al., 2011; FAO, 2012). It represents an important technological measure in agricultural production to compensate for a shortage of rainfall during the growing season. This shortage can be structural and physiological whenever there is permanently not enough rainfall to produce yields and it can be temporal with irrigation used episodically for drought mitigation. Irrigation also represents an economic leverage point for farmers to increase yield in environments with natural water stress. These aspects and the fact that irrigation water leaves the system through the atmosphere and cannot be reused make irrigation central to sustainable water resources management. It also calls for widening the term irrigation management from the narrow technical understanding of the management of irrigation systems towards a river basin approach, which

includes issues like optimized allocation of irrigation within a basin, balancing blue water demand and availability as well as upstream-downstream benefit sharing.

Considered from a systemic point of view, irrigation adds complexity to the water-food-energy nexus because irrigation converts comparatively large amounts of blue into green water, which links food production to regional blue water availability. The use of blue water also makes irrigation, and thereby food production, an upstream-downstream issue and creates the strongest spatial interdependencies of all water-food-energy nexus factors. Water connects different geographical regions and transfer valuable energy and water resources from upstream to downstream. As a consequence, water management cannot solely be local. In order to warrant sustainability and maximize welfare of all participants in a watershed, it should be explored ways to identify the most beneficial, efficient and equitable use of the common resource.

Furthermore, climate change directly influences irrigation regimes through changes in blue water demand and potential agricultural yields (Molden et al., 2010; Porter et al., 2014). Regional blue water availability might also significantly change, thereby putting pressure on the regional balance in the use of a basin's land and water resources (Rosenzweig et al., 2014; Iglesias and Garrote, 2015).

Irrigation plays a central role in achieving water, food (and more broadly land) and energy related Sustainable Development Goals (UN, 2015). They are not only strongly interlinked with each other but are also strongly connected with social and economic Sustainable Development Goals (Nilsson et al., 2016). There is no doubt that each goal is meaningful by itself in achieving sustainable development. Nevertheless, today the ways towards reaching them are not operationalized in terms of management and verification. The central scientific and operational challenge in achieving the Sustainable Development Goals until 2030 is how to align the pathways towards reaching each one of them in ways that amplify each other.

The above mentioned aspects are relevant particularly in the context of doubling global agricultural production until 2050, in order to satisfy the demand of a growing and wealthier world population (FAO, 2012). Agricultural production depends on climate and on natural resources of which, land and water are the most important. Rainfall, which hits the land surface is stored in the soils and thereby makes land and water interconnected and partly interchangeable. Access to more rainfall can be granted to agriculture by expanding the cropland area in non-cultivated places. Rainfall can also be used more efficiently on today's cropland through improved agricultural management practices. Finally,

blue water can be added to the rainfall through irrigation to improve water availability to the crops. Since suitable cropland is limited and since most of it is already in use, expansion of cropland area is not considered feasible and sustainable to raise agricultural production (Zabel et al., 2014). This is supported by the need to protect natural habitats and biodiversity. The most promising way to satisfy future demands is to increase input efficiency in crop production.

Gains in water use efficiency (i.e. reducing the amount of water that is needed to produce a kilogram of yield) both in rain-fed and irrigated agriculture, therefore, represent the main pathway towards satisfying future food demands (Mueller et al., 2012; Brauman et al., 2013), including overcoming environmental and economic impacts of unsustainable water use.

Closing the gap between current agricultural production and future demand, therefore, calls for an intensification that is sustainable (Godfray and Garnett, 2014; Mauser et al., 2015). Since the level of intensification that is still sustainable is not easy to define and since this level can vary from field to field only rough estimates exist today on the gap between current yields and a possible sustainable increase in yield. This has been summarized for different countries by Bruinsma (2009) and is shown in Fig. 1.

Fig. 1 shows the difference between the actual (in blue) and the agro-ecologically attainable yield (in red) for wheat. Negative red columns mean that the actual yields are already above the ecologically attainable level, positive red columns mean that reserves exist for sustainable intensification. Three countries in Fig. 1 are part of the Danube Basin: Germany, Hungary and Romania. Whereas in Germany the current yield levels

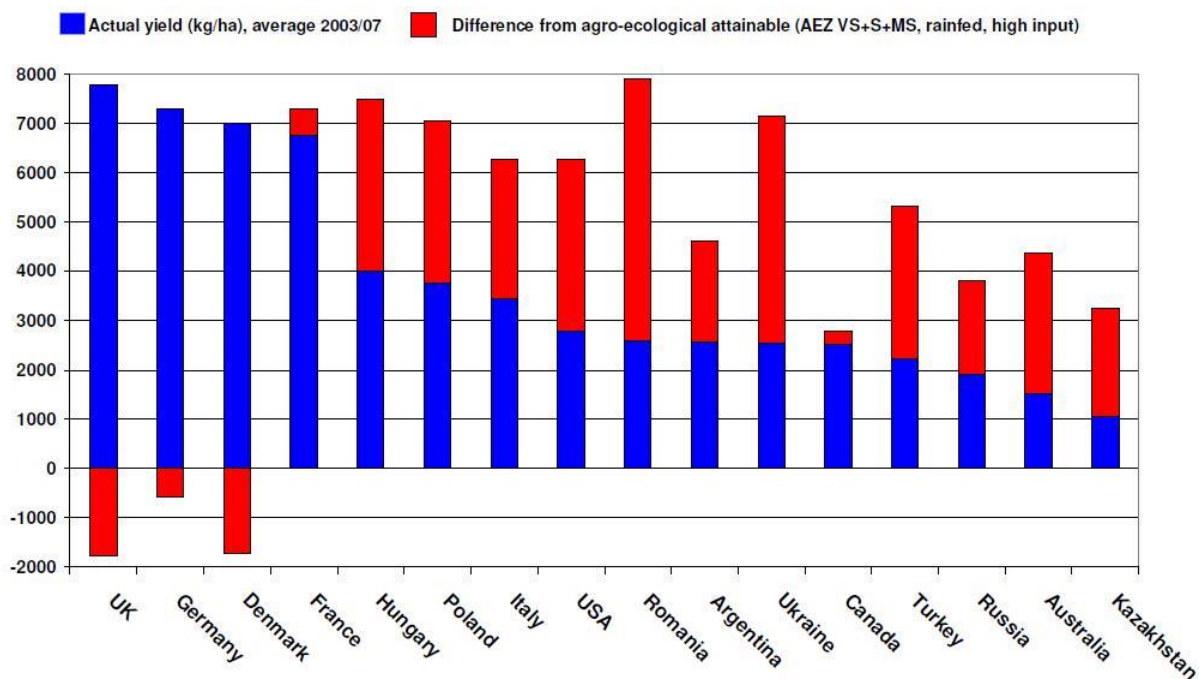


Fig. 1 Difference between actual and agro-ecologically attainable yield for wheat in selected countries, where VS stands for 'very suitable' land for crop production potential (i.e. the attainable yield is 80 to 100 percent of the maximum constrained-free yield); S is 'suitable' land (i.e. 60-80%); MS means 'moderately suitable' land (i.e. 40-60%) (from Bruinsma, 2009). The agro-ecological zone (AEZ) defines a standardized methodological framework for the characterization of climate, soil and terrain conditions relevant to agricultural production (Fisher et al., 2012, 2002)

are beyond the ecological limit, Hungary and Romania still hold reserves of 100% and more for sustainable intensification in rain-fed and irrigated agriculture. This makes it worthwhile to thoroughly examine the Danube Basin for hot-spots for land use change, intensification and increase in water use efficiency.

These aspects call for exploring and developing basin-wide, coordinated and adaptable management approaches which ensure the most beneficial, sustainable and equitable use of blue and green water resources, specifically for irrigation. Spatial and sectoral alignment of the water, food and (renewable) energy management is, therefore, the key for adaptive, sustainable and integrated irrigation schemes, which create both downstream and upstream welfare effects.

How does this translate to river basins within large political entities like the European Union? The EU constituted on the subsidiarity principle and the idea of solving each problem at the institutional scale at which it can be solved in the most appropriate and effective way. How does the idea of managing irrigation in the nexus sense relate to the subsidiarity principle in a situation when the administrative boundaries in a river basin are largely national or provincial and, therefore, do not coincide with the river basin or sub-basin boundaries? How could upstream-downstream benefit sharing from coordinated, basin-wide and adaptive irrigation management be envisioned in such a situation?

The scope of this article is thus to provide a scientific and policy documented source of information for a co-design research approach in which academia and stakeholders concur with plans for sustainable irrigation water use in view of integrative resource management in the Danube Basin.

STUDY AREA: THE DANUBE BASIN

We chose the Danube Basin to assess the current situation of irrigation and its potential future role as an exemplary case study to show the current knowns and unknowns on

the way towards a coordinated, basin-wide and adaptive future irrigation management. The Danube Basin is the largest river basin in the EU (i.e. it covers 801 463 km² and hosts about 81 million inhabitants) and the world's most international river basin, being shared by 19 countries.

The diverse natural conditions throughout the Danube Basin impose different shares of croplands in the landscape (Fig. 2), favoring or limiting irrigation application decisions where necessary. As such, the relief characteristics in the Upper Danube Basin, till the Morava River, favor cropping activities in the plains and low hills of the Bavarian Depression in Germany and in the intra-mountain plain, on the long rounded hills and in the high piedmont plains at the bottom of the Alps of the Vienna Basin. In the Middle Danube Basin, specifically in the Pannonian Depression, the agricultural activities are favored by the presence of fertile soils covered by loess, particularly in the large Pannonian Plain in Hungary (i.e. the Middle Danube Plain) which extends in Romania, Serbia, Croatia and Slovakia as well (Loczy et al., 2012). In the Lower Danube Basin which extends in Romania and Bulgaria, one of the most extensive agricultural regions of high productivity potential is the Romanian Plain, including the Danube alluvial plain (52 600 km²). It has large areas of fertile soils of Chernozem type and a high diversity of ecological conditions (e.g. tabular plains covered by loess, piedmont plains, terraces plains, low subsidence areas, Danube terraces which in the western part are covered by sand dunes, etc.) (Romanian Geography V, 2005). In Bulgaria, the relief of the Moesian Plain, including the Danube alluvial plain, turns from flat and hilly in the western part to hilly-plateau toward east. The region is crossed by valleys with high depth phreatic layers, rendering rather difficult conditions for irrigation (Stefanov, 2002).

Rainfall decreases from West to East, from about 700-900 mm to about 400-300 mm. This leads to structural deficits in rainwater availability for agriculture in the Pannonian and, even more markedly, in the

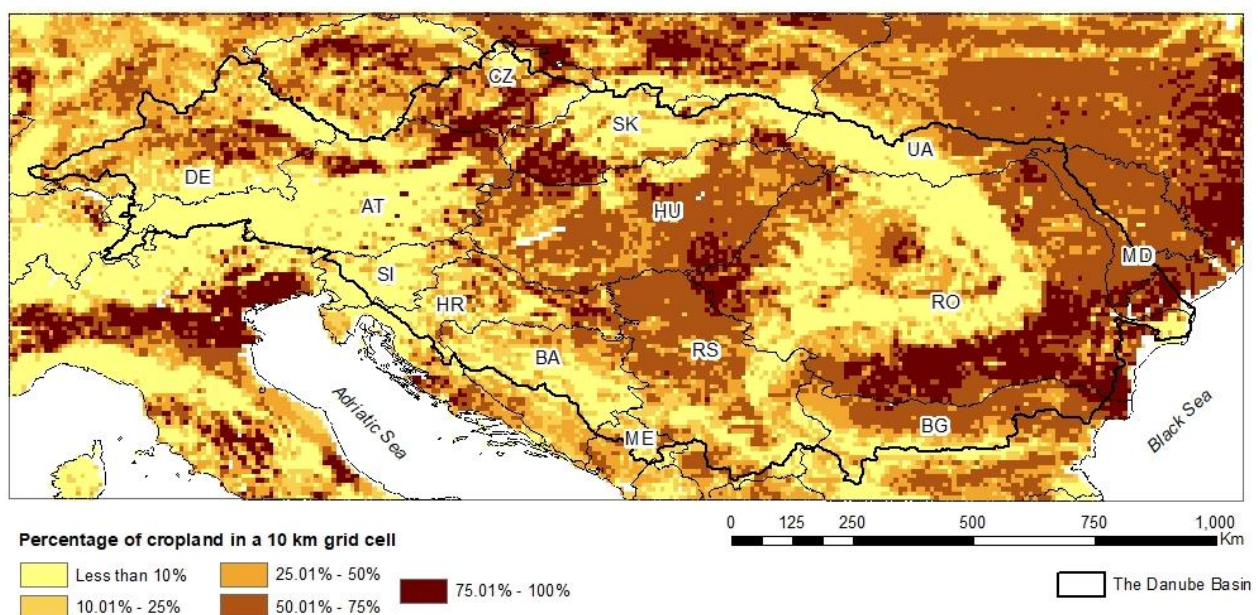


Fig. 2 Cropland in the Danube River Basin, (Dataset: Ramankutty et al., 2010)

Romanian plains. These large and fertile downstream areas of the Danube Basin can improve from irrigation to increase yields by reducing or mitigating water stress in summer and by increasing resilience against droughts, which will most likely be more frequent in a future climate. Large irrigation systems had been installed during communist times (i.e. 1960 – 1980s), proving the necessity for irrigation in these regions. They largely turned inoperative, particularly in Romania, during the transition period towards market economy (i.e. 1990s), while a possible relaunch would open up opportunities to establish new sustainable irrigation schemes in large parts of the basin. Governance schemes are in place on the EU (Framework Directives), the basin (International Commission for the Protection of the Danube River – ICPDR; Danube Strategy) and on the national, province and county level to manage the water, food, (renewable) energy and land resources. We assume that these multiscale governance schemes contain large untapped potentials for alignment and spatial interconnection.

Climate change is an important driving force that affects nexus resources and induces strong spatial differences within the Danube Basin (ICPDR, 2013; Mauser et al., 2018). Temperature increase, variation in rainfall amounts and their changing distribution patterns are expected to cause significant modifications in the hydrological regimes of the Danube sub-basins, resulting in more frequent periods of severe low flow conditions and decreasing summer discharges in the Upper Danube (Mauser and Hank, 2008; Mauser and Prasad, 2016) and more frequent, longer and intense drought periods in the Lower Danube (CLAVIER, 2009). Such impacts are likely to affect the water balance of the entire basin and the sub-basins and lead to increasing stress on the water resources, which further result in impacts on actual evapotranspiration and increase of irrigation water demand, while decrease the flow in rivers which are main sources for irrigation (Pistocchi et al., 2015; Bisselink et al., 2018). At the same time climate change and elevated CO₂ concentrations will strongly affect the agricultural yield potentials in the basin. On the one hand climate change will generally decrease water availability on the other hand however, increasing CO₂ levels will improve water use efficiency for most agricultural crops. The net effects on yields can be very diverse regionally and the potentials are not known yet in detail. Most likely, the land use and irrigation regimes in the Danube Basin will be strongly influenced.

In view of the above-mentioned arguments, the Danube Basin is ideally suited for our study because it offers a complex web of (historical) regional needs for irrigation, climate gradients and climate change, multiscale institutional settings, different farming practices in the Danube countries, and different economic development dynamics.

IRRIGATION AND WATER-FOOD-ENERGY NEXUS IN THE DANUBE BASIN

Insights on irrigation sector in the Danube countries in relation to water-food-energy nexus were derived from profiled literature referring to topics such as: agricultural

drought and management, water use efficiency, water scarcity, virtual water, and climate change implications on water resources. Furthermore, we documented the European Union's and national existing regulations, norms and future development plans with respect to water management, including irrigation water use. These aspects are described in the section below.

EU/Danube Basin interdisciplinary research projects

European Commission (EC) signals that water scarcity and drought have become growing challenges for many parts of Europe over the last decades, generating increasing costs and damages and potentially leading to changes in irrigation water regimes, particularly in the Lower Danube (EC, 2009, 2012; Pistocchi et al., 2015). Water scarcity, drought, desertification and climate change impacts and the associated risks in Europe, including Danube countries, have been assessed over the last decade in a number of EU interdisciplinary projects (e.g. CC-WARE, CLAVIER, SEE-RISK, RE-CARE, IMPACT2C, MACSUR, DROUGHT R & SPI) funded by EU-FP6, EU-FP7, ERDF or Cohesion Funds. Broadly, this research covers drought risk management topics, with a focus on impact assessments on cropping systems and farmers in most drought-affected regions of Europe (GWP CEE, 2015; MACSUR, 2017; Siebert et al., 2017), as well as on characteristic drought indices representation under current and climate change conditions (Blauhut et al., 2016).

The latest projects funded through the Interreg Danube Transnational Programme (i.e. Interreg DTP, a funding instrument targeting the Danube Region in particular), e.g. DriDanube DTP, whose objective is the assessment of drought related risks in the Danube Basin, and CAMARO-D DTP, with a focus on the assessment of land use impacts on water regimes in the Danube River Basin, serve as examples of investigating optimum options of land and water integrative management through several case-studies.

Moreover, the growing signals of water scarcity, which is prospective in the case of the Danube Basin under climate change (Pistocchi et al., 2015; ICPDR, 2015; Bisselink et al., 2018), suggest a stronger emphasis on the international or regional trade of food and products in the context of virtual water (i.e. the green and blue water used in producing the commodity) concept. For example, the Danube Basin could shift from a net virtual water importer into a net exporter under particular dietary scenarios considering only the case of the agricultural products (Vanham and Bidoglio, 2014).

A number of European database structures (e. g. EURO-CORDEX and predecessors, CarpatClim, EC EUROSTAT and EC Joint Research Center portals) provide domain parameters such as climate variables and impact climatic indices, as well as comprehensive environmental and socio-economic indicators. Worth mentioning the FAO AQUASTAT dataset which offers statistics and gridded data at 5 minutes grid-cell resolution (about 10 x 10 km² near the equator) on irrigated areas and areas equipped for irrigation (Döll and Siebert, 2000; FAO Aquastat, 2013). However, the need for accurate monitoring of irrigated areas in Europe with the support of the Global Monitoring for Environment and Security

Programme (GMES/COPERNICUS) and its fleet of remote sensing satellites is expressed by European Commission's aims towards achieving water use efficiency (EC, 2012).

Scientific information at regional and national level

The contextual literature on irrigation has been informing on the particularities of the irrigation sector in the Danube countries, particularly in the Lower Danube where irrigation has a long tradition. While the syntheses on irrigation remain valuable sources of information in terms of past developments of the agricultural infrastructure, crop suitability and environmental impacts in irrigated areas (Grumeza and Kleps, 2005; Bárek et al., 2009), the local case-studies provide details on the conditions and parameters of various agricultural regions for optimum irrigation schemes, such as timing, watering norms, water use efficiency in irrigated vs. rain-fed conditions, etc. The results of numerous empirical studies and field experiment applications concerning irrigation water use for most common crops under various local conditions in the Danube Basin are found in the annual series and communications published in the journals and bulletins of specialized institutions, such as the National Research Institute of Agriculture in Romania, the Agricultural Faculties (e.g. Scientific Papers. Series A. Agronomy, 2012 – 2017) or the Slovak Agricultural University (e.g. Acta horticulturae et regiotecturae).

However, only few landscape scale studies in the Danube Basin provide evidence on the influence of the changing climate conditions on water resources and agricultural productivity, and in the context of increasing demands for food, water and bioenergy. For instance, GLOWA-Danube project represents an example of integrative assessment of the regional effects of climate change in the Upper Danube. It is based on an integrative decision support system (i.e. DANUBIA) consisting of various natural based and social science based sub models which allow the design and assessment of complex scenarios for future development, envisaging impacts on water resources (Mauser and Prasch 2016). Likewise, the ICPDR case study on Tisza River Basin, in the Middle Danube region, stresses the importance of integrated management of water and land resources due to the impacts of agriculture resulted from water abstractions and nitrate pollution (ICPDR 2012). Moreover, the ICPDR Report (2017) on the 2015 drought points out that agriculture was by far the most affected sector and in areas with periodical irrigation, such as the Marchfeld in Austria, water demand was significantly above the long-term average. The Report concluded that water scarcity is likely to increase in the Danube Basin, drought will be one of the future priorities in water management, better data monitoring for agricultural water withdrawals and, enhanced dialogue between the water and the agricultural stakeholders are needed.

EU/Danube Basin regulatory frameworks

The regulatory framework for the Danube Basin management has been constantly developed since the Danube River Protection Convention was signed in 1994 in Sofia (BG) by the riparian countries. Focusing in the

beginning on the quality of the water and environmental protection, it evolved, up to present, toward the integrative management framework of ICPDR. The latest river basins management plans in the Danube Basin represent a common effort of the Danube countries to work on and respond to integrated land and water management requirements, considering future water demands and climatic conditions (ICPDR, 2015).

The Water Framework Directive (WFD) in particular targets long term actions such as protection of waters so as to achieve a qualitatively and quantitatively good status of all waters in Europe, including efficiency of water use, adequacy of agricultural practices and coordinated water-pricing policies. Likewise, certain EU's Common Agricultural Policy (CAP) subsidies are contingent on meeting the objectives in WFD through Cross Compliance and agri-environmental measures with the purpose of decreasing the agricultural pressures caused by water abstractions and hydromorphological changes, thus enhancing the synergies between water and agricultural policies (EEA, 2012). At the same time, CAP aims at ensuring food security, climate adaptation, a competitive and dynamic farming sector and green economy by supporting the economic growth while preventing environmental risks (EC, 2010). It is acknowledged that sustainable agricultural measures can support water management through sustainable farming practices. More efficient water saving irrigation techniques will have to be developed and applied along with sustainable regulatory actions envisioning water use with special attention to water demand to prevent or effectively respond to water scarcity challenges (ICPDR, 2015).

Although the principles of the European water and land use policies are meaningful, their implementation throughout all member states (including Danube countries) is a complex and difficult process. It relates to integrative management of resources and active transboundary cooperation in the context of sharing resources among countries. Such aspects are not straightforward, but marked by complex trade-offs among sectors or risks induced by market mechanisms which usually are oriented towards achieving greater profits, or by regional particularities (e.g. economic evolution pathways, cultural legacy, governance structures, etc.) which may make particular legislation problematic for one country but suitable for another. Nevertheless, achieving cross-sectoral and cross-scale cooperation for an integrative and sustainable resource management is dependent on the political will, stakeholder commitment and working institutional arrangements to manage resource nexus issues (Hoff, 2011; Allouche et al., 2015).

National regulations and development strategies for irrigation in the Danube Basin countries

This section synthesizes the main aspects regarding irrigation management and irrigation future development plans in the Danube countries where irrigation has been playing an important role for agriculture and represents central issue for climate change adaptation and mitigation strategies (Table 1).

Table 1 Schematic information on irrigation regulatory designs and perspectives in the Danube basin's countries

Country	Current situation (brief note)	Regulatory instruments for irrigation	Development perspectives
Germany	DE is relatively rich in water resources. Recent experience in irrigation due to increasing drought spells.	Permits are needed to allow for the abstraction of an allotted volume of water for irrigation (Germany's Federal Water Act).	No specific development plans for the German part of the Danube (i.e. Baden-Württemberg and Bavaria). However, the federal states make use of the subsidizing options to a very varied degree (Bosch & Partner GmbH, 2014).
Czech Republic	The actual use of the irrigation systems accounts for about 25–30% of the area equipped with irrigation which is of 160 000 ha, i.e. 3.65% of agricultural land (Trnka et al., 2016).	Irrigation water is used on the basis of permits for water abstraction; payments are applied for abstractions larger than 6 000 m ³ /year or 500 m ³ /month.	The rehabilitation of the existing infrastructure and development of new systems are envisaged in view of future increased areas affected by precipitation deficits due to climate change (Trnka et al., 2016).
Slovakia	Initially covering 321 000 ha (~20% of arable land), the operational systems nowadays can cover 72 565 ha (Hydromeliorácie, š.p. Report, 2016).	The Ministry of the Environment has introduced a fee with the lowest possible impact for irrigation water consumption (Act no. 303/2016).	An increase of the irrigated area to 892 000 ha, or at minimum to 700 000 ha, is required in order to prevent climate change effects (Konceptcia, 2014).
Hungary	Water sources are based on transient waters. During 2009 – 2011 about 70 000 ha were irrigated and in 2015, 128 328 ha (i.e. 2.4% of the agricultural area) (EC, 2015).	Permits for irrigation are issued by the General Directorate of Water Management / subordinated institutions on the basis of contracts for irrigated areas.	To minimize the effects of drought, it is expected that the irrigation area could increase to about 180 000 ha, although there is a great uncertainty about the required water quantities abstracted for irrigation (ICPDR, 2012).
Republic of Serbia	Transient waters are sources for water abstraction for irrigation; the irrigation systems cover a relatively small area of cultivated land (i.e. 105 000 ha out of 2 016 716 ha of arable land) (MAEP, 2015a).	Water permits are issued for land owners or suppliers of irrigation water for a certain amount of abstracted water. Farmers pay half of the tariffs set out for the irrigation.	The irrigation area is going to increase to 350 000 ha by the end of 2030 through rehabilitation of the existing systems and construction of new infrastructures, along with nonstructural measures (e.g. knowledge transfer, consultancy for farmers, etc.) (MAEP, 2015a).
Romania	It benefits from a large experience in irrigation. During 70s–80s, an extensive irrigation system was installed, i.e. ~ 3 million ha out of 9 389 200 ha (INS, 2015). In the recent past (2009 - 2016) about 600 000 ha totals the land that could be irrigated (AFIR, 2017).	A yearly subscription for an allotted volume of irrigation water was available until recent to farmers (Law no. 138/2004, amended by Law no. 158/2016). Presently, the costs for irrigation water (i.e. the costs of water and energy for pumping) are totally subsidized (Law no. 133 / 2017).	The National Programme for the Rehabilitation of the Primary Irrigation Infrastructure of the Ministry of Agriculture and Rural Development (MADR, 2016) stipulates that 2 006 941 ha are going to be suitable for irrigation by 2020.
Bulgaria	Built during the 60s – 70s to cover about 740 000 ha (Velikov, 2013), the irrigation systems serve today only between 4% and 8% of the irrigable area, i.e. 541 779 ha (Ministry of Agriculture and Food, 2017).	Permits to abstract an allotted volume of water for irrigation issued according to the Water Act's conditions for water availability and sustainable use. The price for the irrigation water delivery service is determined annually by the Minister of Agriculture and Food (Decree No 16/20.01.2017).	The Strategy for the management and development of the hydraulic network and protection from harmful effects of water aims to increase the actual irrigated area by 2030 to 316 580 ha (Ministry of Agriculture and Food, 2016).

DISCUSSION ON THE CHALLENGES TO IRRIGATION WATER USE IN THE DANUBE BASIN

Irrigation in the reported data on water use

Reported data, where available, on water use in the Danube countries were analyzed in order to get an overview on the level of water demands in the basin, as well as on the possible gaps in data monitoring for sustainable irrigation management.

The shares of surface water abstractions from the Danube River Basin relative to the total surface water abstractions in each country highlight those countries dependent on Danube's water resources given their largest extent in the basin, i.e. Hungary, Romania, Slovak Republic, Serbia (Table 2). However, Danube Basin's surface waters are used according to each country's level of water resource availability, demand and supply endowment facility, ultimately depending on the environmental conditions and the socioeconomic development of the country.

Table 2 Volumes of fresh surface water abstraction from the Danube River Basin by country, total and by sectors, in million m³, and as percentage of the country's total fresh surface water abstraction, in brackets. The percentages in the square brackets represent the fresh surface water abstraction from the Danube River Basin relative to the renewable freshwater resources existing in the respective country.

Danube country	Total gross abstraction	Public water supply	Irrigation	Production of electricity (cooling)
DE	3 181.70 (11.71%) [6.92%]	59.07 (3.90%)	-	-
CZ	194.54 (13.16%) [6.45%]	35.30 (10.54%)	12.25 (59.96%)	76.06 (11.93%)
SK	283.97 (99.12%) [0.35%]	46.38 (95.26%)	12.08 (100.0%)	-
HU	4 956.20 (100.0%) [4.28%]	255.20 (100.0%)	109.29 (106.1%)	3 862.43 (96.13%)
RS	1 288.87 (36.31%) [0.74%]	97.35 (48.26%)	40.20 (56.04%)	1 086.25 (34.54%)
RO	5 860.46 (100.0%) [15.03%]	606.14 (100.0%)	352.70 (100.0%)	1 050.11 (100.0%)
BG	2 931.05 (54.60%) [2.83%]	293.53 (60.11%)	20.42 (7.05%)	2 522.96 (73.18%)

Source of data: EUROSTAT, <http://ec.europa.eu/eurostat/data/database>; the data for most of the countries are averaged around the year 2011. The countries were considered based irrigation application relevance for the respective country (see Table 1) and on data availability, e.g. no EUROSTAT data for fresh surface water abstraction were available for Austria.

Romania stands out as the largest consumer of fresh surface water for irrigation among the Danube countries, considering only the Danube River Basin resources. However, this aspect is not reflected by the yield levels (e.g. in Romania maize achieves a yield of 4 t/ha as compared to 7.4 t/ha in HU; EUROSTAT, 2017). This is related to inefficient irrigation water use due to aspects such as low technical capacity of the existing irrigation infrastructure, lack of cooperation between the water suppliers and farmers resulting in improper timing and norms of irrigation application, etc. (MADR, 2011). In essence, the extensive irrigation systems are characteristic for the large agricultural areas in the Middle and Lower Danube Basin, e.g. Hungary and Romania, where the infrastructure has been planned for large scale irrigation application. The climatic scenarios studies show increasing intensity and frequency of droughts particularly for Central and Eastern Europe (CLAVIER, 2009), thus requiring a careful allocation of water resources specifically in this part of the basin.

The data shown in Table 2 gives a first overview on the currently available knowledge on the diversity of irrigation in the Danube River Basin. It conveys two clear and important messages: 1) although all countries extract irrigation water from the common Danube water resources, data is largely available only on the national level, no comprehensive and homogeneous data set is available on the irrigation in the Danube Basin, 2) the reported data is strictly based on registered values of water that is metered for irrigation. It contains no information on how much of this irrigation water is productively used for the purpose to increase yields. From a water-food nexus perspective this aspect is bound to create confusion on how much water is actually consumed by irrigation at a certain location and on how much of the extracted water, which is metered, can in principle be used further downstream because it is not leaving the system.

Fig. 3 shows the irrigation water pathway from a resource nexus point of view. Water for irrigation must be extracted from a river or a groundwater aquifer and is

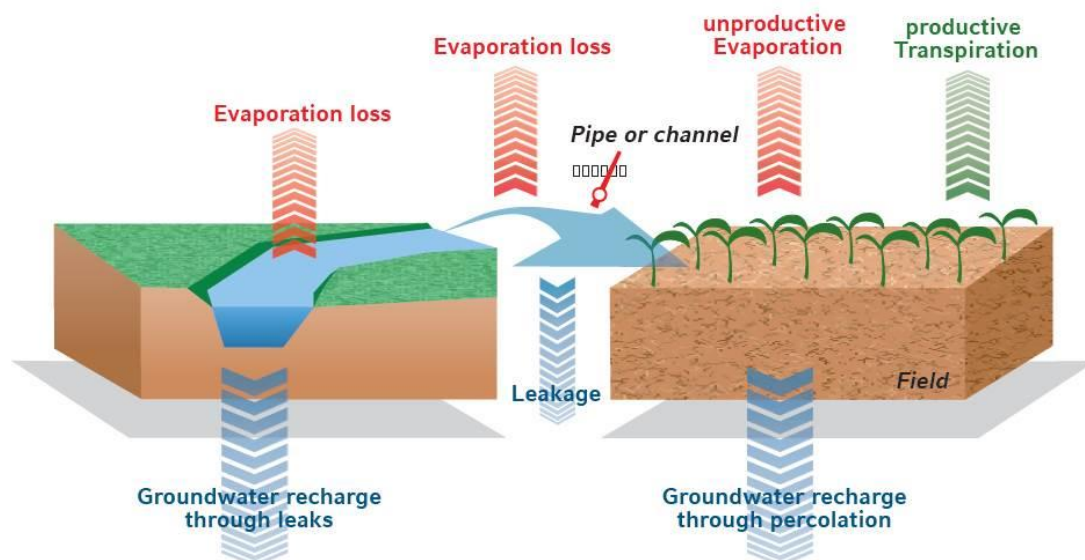


Fig. 3 Irrigation water pathway in the context of resource nexus

usually transferred to the point of use through open canals. The losses occur in the form of evaporation from the open water surfaces and leaks from the canals. These two losses are distinctly different from a nexus point of view. Whereas the water that leaks from the canals stays in the watershed and can in principle be harvested from the groundwater at a downstream location and is therefore not lost to the system, the evaporated water from the open waterbodies leaves the basin as part of the atmospheric circulation and is therefore lost for any alternative use in the basin. The water that is transported on the irrigated fields is metered and serves the basis for the statistics. On the fields, again, access water leaks to the groundwater and stays in the system, whereas (unproductive) evaporation from the ground and wetted leaves exits the system without effect on plant growth. Only the water that transpires through the plants, although it is lost to the system, has the desired irrigation effect to support plant growth. Inefficient irrigation water use therefore has two aspects: 1) the unproductive evaporation of water, which leaves the system, 2) the unproductive leakage of irrigation water into the groundwater; here the water stays in the system. Clearly from a water-food nexus point of view both pathways have to be minimized. Nevertheless, there is a fundamental difference between the two pathways, both in the consequences to the system and in the measures necessary to minimize the pathways. This is particularly important when water use issues involve shared waters. Therefore, the first pathway (i.e. unproductive evaporation) unnecessarily destroys water resources upstream and deprives the downstream users of water resources that would in principle be available. The second pathway (i.e. unproductive leakage) usually diverts water from surface to groundwater storage and leaves opportunities open for the downstream users. Unfortunately, these pathways are not reflected in the metered irrigation water use. This prevents a regulatory and governance framework which can adequately balance water availability and allocation of water to irrigation upstream and downstream and among different countries.

Framing a transdisciplinary research in the support of a basin-wide irrigation management plan

The tendency in the irrigation sector in the Danube countries is to increase the irrigated area and to offer legislative and financial support for encouraging the use of the already existing irrigation infrastructure and for the development of new systems. In Romania, for instance, increasing the irrigated area from about 0.5 million ha that can be irrigated today to almost 2 million ha by 2020 is an ambitious objective which aims to boost agricultural activities and production, contributing also to climate change adaptation and rural communities' resilience. In Bavaria, although it is not allotted a certain area for irrigation, the expected increase in water withdrawals for irrigation in the context of climate change is already an issue on the decision makers' agenda. Under these circumstances, central questions have to be addressed:

- If all Middle and Lower Danube countries implement their plans to expand irrigation, can water availability sustainably meet the created demands?

- Where in the upstream-downstream context will hot spots of water shortage be created?
- What will be the impact of climate change in altering the availability-demand relation in the Danube Basin?
- What role must advance irrigation monitoring systems, which are able to distinguish inefficient irrigation water pathways, and advanced irrigation technologies play to ensure sustainable irrigation and upstream-downstream benefit sharing?
- What governance concepts, including irrigation water pricing strategies, are effective and efficient in reaching the goal of maximizing the societal benefit of irrigation water for the whole Danube Basin?

Moreover, the paper highlighted a series of issues related to irrigation in the Danube Basin, such as: no basin-wide irrigation assessment is available for the Danube; the statistics express the irrigation water that is metered and not the water that is actually consumed to produce food; the EU legislation with respect to water and land resources, although profoundly integrative in character, is still difficult to be implemented in all Danube countries, raising complex resource trade-offs issues; irrigated agriculture in the Danube countries is significantly subsidized, fact that might further enlarge the economic and development disparities in the Danube Basin, although such measures are welcome by farmers; and, climate change impacts on irrigation are only known with a large degree of uncertainty.

Increased irrigation, profitable agriculture and climate change are common issues for all Danube countries. In this context, the question how Danube countries can solve irrigation and drought problems in a sustainable way is a transdisciplinary research endeavor as much as it is a cooperation and governance challenge, dealing particularly with the synergies and trade-offs of water for agriculture, hydropower, navigation and domestic use. To this end, the implications of water abstraction for irrigation in the Upper Danube countries on the availability of water resources for the downstream countries represent a research question that holds multiple cross-sectoral consequences (Mauser, 2017). This is connected to the topic of changing virtual water flows within the Danube Basin, being subject to scenario assessment in order to identify the optimal economic and social resolutions for all Danube countries (Vanham and Bidoglio, 2014). Collaborative efforts between academia and various stakeholders at different level in co-designing this type of knowledge is part of a solution-oriented research which goes beyond complex models, systemic and interdisciplinary problems to englobe in the research process developmental objectives, norms and visions which altogether aim at producing legitimate knowledge and guidance for intervention strategies (Mauser et al., 2013).

Considering the above-mentioned considerations on irrigation in the Danube Basin, we identified 6 interconnected themes for evaluating irrigation water use at a basin scale which could form an integrated research framework (Fig. 4). These are summarized below.

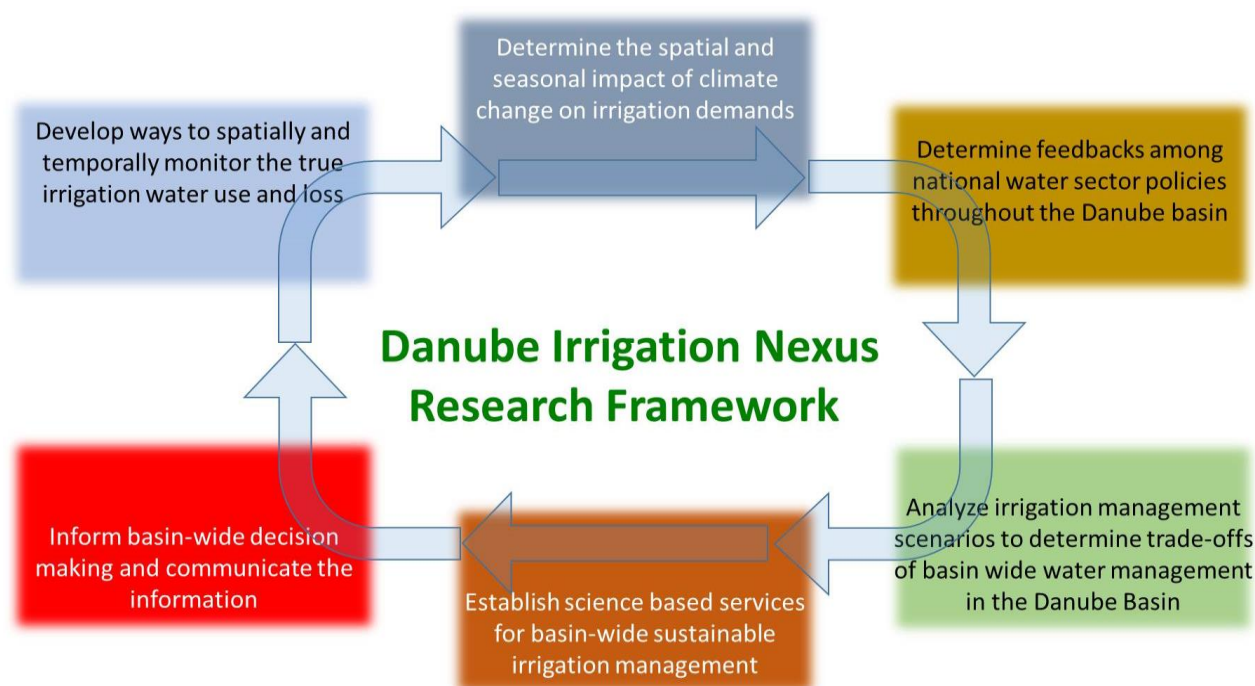


Fig. 4 Outline of the „Danube Irrigation Nexus Research Framework” for co-producing scientific knowledge for a basin-wide sustainable irrigation management plan

1) a basin-wide monitoring system that reflects the amount of irrigation water that is actually consumed by the cultivated crops as well as the additional amount of water needed to combat soil moisture deficits. The novel, basin-wide monitoring system can roughly be based on a combination of crop growth modeling and remote sensing time series taken from the available COPERNICUS satellites, in which the observed growth patterns on irrigated and non-irrigated fields are compared with simulations of plant growth and yield, from which real irrigation water consumption is determined by considering available rainfall;

2) climate change impact assessments on Danube Basin water resources highlighting potential regional hotspots of water shortages and its consequences for irrigation. This part is based on extensive basin-wide simulations of crop growth under current climate and future climate scenarios including CO₂ fertilization effects and determines the spatiotemporal distribution additional irrigation water demand;

3) the co-design (with relevant stakeholders) of scenarios of future development alternatives and their simulation in order to explore, in a transparent way, feedbacks (positive and negative) among national water policies / management decisions in agriculture (including irrigation), energy, industry, public use and ecosystem protection, with a special emphasis on exploring the mechanisms of upstream-downstream benefit sharing;

4) based on the scenario analysis, the trade-offs of decision alternatives are identified for sustainable water uses based on an active cooperation between stakeholders at different governance levels and academia;

5) derivation of science-based services for basin-wide irrigation management;

6) dissemination of scientific outcomes for informed decision-making at national and regional levels.

The above “Danube Irrigation Nexus Research Framework” relies on sophisticated new monitoring and simulation tools using the available COPERNICUS satellite data streams and smart environmental models. Nevertheless, at its core is the co-creation of knowledge on sustainable basin-wide irrigation water management, which is based on an intensive stakeholder cooperation process, which ensures that the practical benefits of a basin-wide nexus approach become transparent to the decision makers and the knowledge is created with the applicability of the results in mind.

CONCLUSIONS

The results of our regulatory mapping and literature review exercise for irrigation water use in the Danube Basin shed light on what is known on irrigation and its future in the basin. It shows the contributions of EU regulations, strategic plans and visions to resource management, including climate change effects on water resources, and the characteristics and conditions of the national regulatory frameworks related to irrigation application in the Danube countries. The challenges of the irrigation sector in the context of future developments and the implications for water-food-energy nexus are derived, ultimately leading to a proposed transdisciplinary research framework supporting a basin-wide irrigation management plan.

The scientific interdisciplinary projects form a rich heritage of data and conceptual and analytical outcomes proving substantial scientific support to base European resource policies and/or aid countries enabling regulation change towards resource sustainability. However, many of them deal with the impacts on resources by sub-systems (e.g. drought and agriculture, water and land use, or energy and water), being difficult to trace the entire

chain of synergies and trade-offs within water-food-energy nexus due to the complex interlinkages between the resources. The research projects do not explicitly approach the issue of irrigation in the Danube basin by considering basin's water availability and resources nexus issues and the trade-offs among them.

Instruments such as allocation of important national and European structural funds for the rehabilitation of the existing infrastructures, governance and institutional (re)arrangements to ensure irrigation management and support of investments in on-farm irrigation systems were implemented. This is specific for Romania, a Lower Danube country with large irrigation application potential and need. In the Upper Danube, irrigation increased particularly as a response to changing climatic conditions. According to the future irrigation development plans, the irrigated areas are expected to increase throughout the Danube countries, the largest areas being located in the Middle and Lower Danube, affecting, therefore, the water balance of the entire Danube Basin.

The scientific information reflects several key points, highlighting the need for increased trans-national understanding of irrigation issues and implications for water resources management at Danube Basin level. Foremost, there is growing evidence that Central and Eastern Europe, particularly Lower Danube, is increasingly affected by droughts which under current development trajectories and climate change impacts will inevitably lead to *water scarcity problems*. Water scarcity, which means using more water than naturally renewable, is a driving force of long-term economic damages (ICPDR, 2015). Moreover, the impact of agricultural drought (i.e. insufficient soil moisture) on *crop yields losses* is not sufficient investigated to support agricultural sustainable practices, climate change adaptation and integrated resources management. Heavy precipitation events and impacts on yield losses and soil are also priorities in some Danube agricultural areas. At the same time, large agricultural areas in the Danube Basin (e.g. Romania, Hungary) benefit from arable land whose *production potentials* need to be accurately quantified to be sustainably exploited in view of both future climatic conditions and socioeconomic development pathways. *Integrative outcomes* regarding water consumption and agricultural production and active collaborations between academia and stakeholders for a *better use of the available scientific knowledge for proactive decision-making* need to be fostered. At present, the proactive measures meant for long-term sustainable development (e.g. enhancing the resilience of the agroecosystems to climatic extreme events) are less envisioned, lagging behind the reactive actions that are taken at times of crises (e.g. compensations for agricultural losses due to drought) (GWP CEE, 2015).

At the same time, water pricing could play a significant role for the improvement of irrigation water use. The potential physical scarcity of water (e.g. supply is affected by more variability and uncertainty due to climate change), its connectedness nature and its common pool resource character might interfere with efficient resource allocation and lead to market failures (Livingston, 1995), e.g. neglecting environmental impacts

or underpricing of the resource (Johansson et al., 2002). Therefore, institutional arrangements have to be set up in order to achieve efficient water use, which means, in an economic sense, to equate the marginal benefits to the costs of the last unit of water used (Johansson et al., 2002). Supporting efficiency requires policy instruments that foster security and flexibility with regard to water rights and that consider the natural interdependency of water users (Livingston, 1995).

In this context, the development of a basin-wide irrigation management plan is a way forward to increasing water use efficiency and to sustainable development at large. Therefore, this paper outlines a research framework that advocates transdisciplinary studies, entailing integrative results on Danube Basin's water-food-energy nexus in which irrigation plays a central role, and where water resources governance could be realized by accounting for the spatial interconnectedness and equitable use of shared resources, aspects that are embedded in the European resource policies and strategies as well as UN Sustainable Development Goals.

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ASSESSMENT OF RUNOFF AND DRAINAGE CONDITIONS IN A NORTH BANAT SUB-CATCHMENT, NORTH-EASTERN SERBIA

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Abstract

The lowland area of the southeastern part of the Carpathian Basin is exposed to extreme hydrological conditions. The monitoring and analysis of the excess inland water are necessary in order to understand the scope and direction of the development of this type of flooding. When solving the problem of the drainage of an area and dimensioning drainage systems, one of the most important steps is to calculate the rate of runoff. Before calculating the rate of runoff, it is necessary to perform various analysis such as: hydrological, hydrogeological, pedological and land use analysis. The use of empirical formulas by different authors is one of the methods for determining the rate of runoff. These formulas can be of regional character, while some are applicable in different parts of the world. In this paper, the runoff coefficient and rate of runoff were calculated as indicators of the efficiency of the area drainage, employing the formulas by Nemet and Turazzo. The emphasis was put on the usage of modern tools and databases of soil characteristics while using a "traditional" method to determine rate of runoff. The obtained results demonstrate that the rate of runoff which reflects the current state of the drainage basin is very similar to the rate of runoff used for dimensioning of drainage system. The problem of retaining smaller amounts of water that remains even after the anticipated drainage deadlines can be solved with the regular maintenance of amelioration canals and additional ameliorative measures.

Keywords: Galacka sub-catchment, drainage, runoff coefficient, GIS

INTRODUCTION

The lowland area of the southeastern part of the Carpathian Basin is exposed to extreme hydrological conditions, therefore the monitoring of the water regime is of great importance on the catchments of this region (Právetz et al., 2015). When it comes to excess water, the two most common forms of occurrence are the vertical type, which occurs as a result of the increase in the groundwater level and horizontal type, which is created by the accumulation of water in the lowest areas. Horizontal type occurs due to difficulty in infiltration and onflow and often is the result of an inadequate application of agrotechnical measures, which lead to degradation of the soil structure, i.e. its compaction (Barta, 2003). Monitoring and analysis of such phenomena are necessary in order to understand the volume and direction of the spreading of this type of flooding and mitigate the consequences for agricultural production (van Leeuwen et al., 2017).

The Vojvodina province, the northern part of the Republic of Serbia, was a wetland area in the past, where after extensive hydro-meliorative works, conditions were created for the development of agricultural production. Construction of riverbanks along large rivers, as a form of protection from high waters and construction of drainage canals as a form of protection from inland waters, water regime regulation is achieved. By the construction of the Danube-Tisza-Danube hydro system, drainage of about

one million hectares of land in Vojvodina has been enabled. Thus Vojvodina became the main production region in the Republic of Serbia (Kolaković and Trajković, 2006).

From the Roman era, the drainage of lowland areas was done by the construction of open canals or different forms of subsurface drainage, which would provide an adequate water regime for the needs of agriculture. However, mechanization of agriculture, abandonment or change the purpose and land use leads to the dysfunctionality of drainage systems (Calsamiglia et al., 2018). In addition, the inadequate function of the system can be the result of climate and hydrological changes that are present in a particular area. Therefore, it is justifiable to periodically analyze the efficiency of drainage systems, which could determine the possible causes of their difficulty in functioning.

During the solving of the problem of drainage of some area and dimensioning drainage systems, one of the most important steps is calculating the rate of runoff. Previously, it is necessary to carry out various analysis, such as hydrological, hydrogeological, pedological and land use analysis. Rate of runoff by its size defines the need for the drainage of some area, and it is directly related to the investments necessary for the construction of such systems (Avakumović, 2005; Kolaković and Trajković, 2006). The use of empirical formulas of different authors is one of the methods for determining the

rate of runoff. These formulas can be of a regional character, while some are applicable in different parts of the world. However, the final choice of the method depends on the availability of input data (Kang et al., 2013). In this paper, using a series of empirical formulas, which were given in the 1965 Main Project of the drainage of the Kikinda Canal catchment (Galacka sub-catchment), the calculation of the runoff coefficient and the rate of runoff was performed as an indicator of the drainage efficiency of the area. The focus is on combining modern tools and databases on soil characteristics and land use with a "traditional" method for determining the rate of runoff. The obtained results should indicate whether this drainage system adequately performs its function in the current hydrological and agroecological conditions.

STUDY AREA

The North Banat once represented the flooding area of the unregulated Tisza river and the delta of Moriš river. After regulating the mentioned rivers and their tributaries, as well as the construction of riverbanks along river streams, there was a need for inland waters drainage. The Kikinda Canal is the northernmost canal of the Danube-Tisza-Danube hydro-system, and its catchment is divided into 24 subsystems. Drainage is carried out by gravity in 20 subsystems, at total area of 418.52 km², while in combination with gravity and pumping stations, excess water is discharged from 4 subsystems, at total area of 432.40 km² (Pantelić, 1965). The land reclamation works in the subject area start from the moment of regulation of the river Tisza and its tributaries till the present day.

The Galacka sub-catchment covers an area of 32.74 km². The total length of the canal network is 67.8 km. The water from this system is drained by gravity or by pumping station, depending on the water level in the recipient the Kikinda Canal. This sub-catchment also includes an area of 4.42 km² of lowland along the Kikinda Canal, northern from the recipient. This area is drained by a peripheral canal, which is 10.5 km long. The position of the Galacka sub-catchment is shown in Figure 1.

From the pedological point of view, the types of soil occurring on the Kikinda Canal catchment can be divided into three groups: zonal soils formed under the dominant influence of the climate, intrazonal soils formed predominantly under the influence of relief and basic rock mass, as well as genetically undeveloped and poorly developed soils (Pantelić, 1965). The first group includes chernozem with all its varieties. The second group includes marsh soil and its varieties, while the third group includes alluvial soils and sands. The geological base of these soils are the loess and the hydrological formations of the Tisza and Moriš rivers, which occur on the fractions of sand, gravel and clay. The loess is mainly wetland origin, made under the influence of winds and sedimentation in the water. Its characteristic is that it has a low permeability power and contains a higher percentage of clay particles, which is the main difference from the typical loess.

At the territory of northern Banat, there is a series of wells in which the groundwater level ranges from 1.5 to 4.0 m below the terrain. Therefore, it can be concluded that the influence of groundwater on the rate of runoff is insignificant (Pantelić, 1965). The climate of this area is

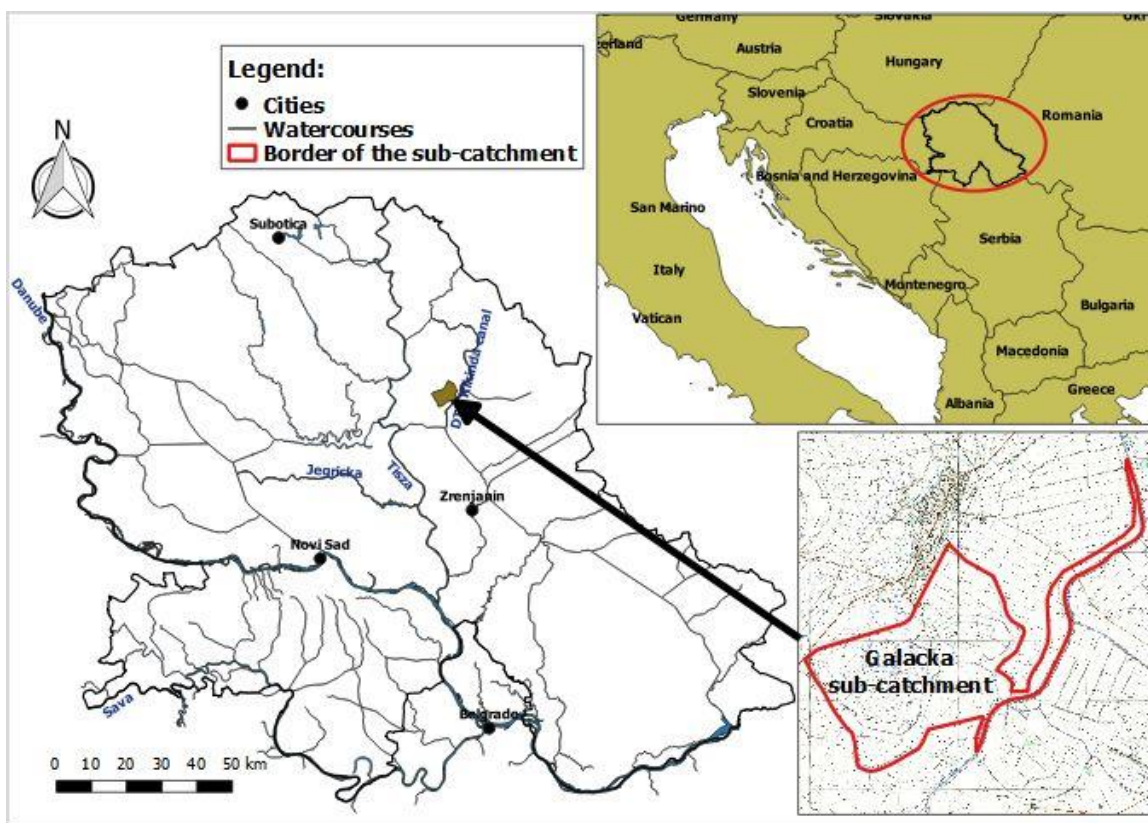


Fig. 1 The position of the Galacka sub-catchment

moderately continental, with a mean annual precipitation of about 560 mm for the observed period 1971–2010. The area is of a very rural nature, where almost 70% of the area is represented by agricultural production.

MATERIAL AND METHODS

The vegetation period rainfall analysis showed that the precipitation in terms of its duration, intensity and uniformity was most conspicuous in May. In April and September, precipitations are by its intensity and duration insignificant. In June, July and August they are higher than the precipitations in May, but also short and uneven (characteristic rainstorms). For these reasons, the rainfalls in May are taken as the most appropriate for estimating the rate of runoff (Pantelić, 1965).

By using the empirical formulas of various authors, obtained from studies carried out in different parts of the world, it is possible to calculate the rate of runoff. In this paper, empirical formulas which were applied in the main project of the drainage of the Kikinda Canal catchment (Galacka sub-catchment) from 1965, were used. In order to determine the efficiency of the drainage of the subject area, the runoff coefficient and rate of runoff are calculated. During the calculation, contemporary databases on pedological soil characteristics (Benka and Salvai, 2006) and type of soil cover (CORINE Land Cover, 2012) were used. Different types of land cover are an important factor in modeling surface runoff (Právetz et al., 2015). The subject of this paper is the functional check of this drainage system in current conditions, taking into account that it was built more than half a century ago.

Water from the Galacka sub-catchment is drained by gravity or pumping station, depending on the water level in the recipient, the Kikinda Canal. Drainage is done by gravity when the water level in the Kikinda Canal is below 75.36 m. At water levels in the Kikinda Canal lower than mentioned, drainage is done through the gravity discharges, and they are 2.0 m³ s⁻¹ capacity. When the water level is higher than mentioned level, drainage is carried out by the pumping station "Galacka", using centrifugal pumps with a capacity of 2.0 m³ s⁻¹ (two pumping units, capacity 1.0 m³ s⁻¹). The pump station is located at km 9+516 on the right bank of Kikinda Canal. For the calculation of the runoff coefficient and the rate of runoff in the Main drainage project (Pantelić, 1965), the formulas given by the authors Nemet and Turazzo were used. This method was used in the middle of the last century, mainly for drainage system designing in the area of Vojvodina (northern part of Serbia) and Hungary. The following are the steps used in analysis of this drainage system.

The following formula is used for the calculation of the mean rate of runoff:

$$q_s = 0.1157 \cdot \frac{\alpha \cdot h}{t + \tau} \quad (\text{Eq. 1})$$

where are: q_s - mean rate of runoff (l s⁻¹ ha⁻¹), α - runoff coefficient, h - relevant rainfall (mm), t - duration of the relevant rainfall (days), τ - time of concentration (days).

If the previous relation is multiplied by the coefficient that represents the ratio of the maximum and

intermediate flows, and which for the Hungarian conditions is 1.7 (applicable for the territory of Vojvodina), the maximum rate of runoff is obtained - q_{\max} (l s⁻¹ ha⁻¹):

$$q_{\max} = 0.1157 \cdot \frac{\alpha \cdot h}{t + \tau} \cdot 1.7 \quad (\text{Eq. 2})$$

When determining the runoff coefficient, it is necessary to take into consideration the drainage characteristics of the soil, the terrain slope, the way of soil cultivating, as well as soil cover type. In the Main drainage project (Pantelić 1965), it is stated that in the study "Amounts of inland waters" by Dr J. Bogardi, the change in the runoff coefficient by months was given in function of:

- (1) terrain slope (α_1);
- (2) soil permeability (α_2);
- (3) vegetation cover (α_3).

The values of these partial runoff coefficients are given in Tables 1, 2 and 3. The total runoff coefficient is obtained by summing of these three factors:

$$\alpha = \alpha_1 + \alpha_2 + \alpha_3 \quad (\text{Eq. 3})$$

Table 1 Partial runoff coefficient in the function of terrain slope (α_1)

Terrain slope	Coefficient α_1
>35 %	0.22 – 0.25 – 0.30
11 – 35 %	0.12 – 0.18 – 0.20
3.5 – 11 %	0.06 – 0.08 – 0.10
<3.5 %	0.01 – 0.03 – 0.05

Table 2 Partial runoff coefficient in the function of soil permeability (α_2)

Soil permeability	Coefficient α_2
Very impermeable soil	0.22 – 0.26 – 0.30
Moderate impermeable soil	0.12 – 0.16 – 0.20
Permeable soil	0.06 – 0.08 – 0.10
Very permeable soil	0.03 – 0.04 – 0.05

Table 3 Partial runoff coefficient in the function of vegetation cover (α_3)

Land cover	Coefficient α_3
Non-covered soil	0.22 – 0.26 – 0.30
Marshes and pastures	0.17 – 0.21 – 0.25
Cultivated soil	0.07 – 0.11 – 0.15
Forests and soils of weak structure (sands)	0.03 – 0.04 – 0.05

For the purpose of determining the partial coefficient α_2 , GIS pedological map of Vojvodina was used (Benka and Salvai, 2006). Coefficient α_2 is obtained by calculating the percentage of different soil types at the subject area and classification according to their drainage

characteristics. The soils are classified into five drainage classes based on the average limit values of their water constants and the main chemical parameters (Miljković, 2005):

- (1) Drainage class I - soil that is naturally very poorly drained, indicating a high risk of excess inland water;
- (2) Drainage class II - soil that is naturally poorly drained, indicating a medium risk of excess inland water;
- (3) Drainage class III - soil that is naturally somewhat poorly drained, indicating a moderate risk of excess inland water;
- (4) Drainage class IV - soils of lighter texture which are naturally moderately well drained, indicating a low risk of excess inland water;
- (5) Drainage class V - soils of light texture which are naturally well drained, indicating no risk of excess inland water as well as no necessity for drainage.

The values of coefficient α_3 have been determined using the CORINE Land Cover 2012 (EEA, 2012) map, which contains data on land cover and attributed areas. GIS tools have been implemented in the analysis of the representation of different types of soil and their land cover, as well as the creation of maps presented in this paper.

Determining the height of relevant rainfall, which is especially used in the prediction of floods with deterministic methods, must be based on the duration of high-intensity rainfall (storm precipitation) or the time of concentration, both for a specific location and a wide area (Gericke and Plessis, 2011). The time of concentration (τ) is a key temporal parameter of basin response, necessary for the prediction of the maximum volume of runoff (Perdikaris et al., 2018). Time of concentration (τ) is the time required for runoff traveling from the hydraulically most distant point in the drainage basin to the outlet, and in the Project (Pantelić, 1965) it is determined with the Venturi formula, where it is expressed in the function of the catchment area:

$$\tau = 0.315 \cdot \sqrt{F} \quad (\text{Eq. 4})$$

where F is catchment area in km^2 .

According to Pantelić (1965) rainfall during the month of May was used in the calculation, and with the Montanari climatic formula which is individually performed for each analyzed area, relevant precipitation levels were obtained using the following formula:

$$h = a \cdot t^n \quad (\text{Eq. 5})$$

where are: h – relevant rainfall levels (mm), a and n – variables that depend on the hydrological characteristics of the analyzed area, while t represents the duration of precipitation (days).

According to Nemet, the duration of relevant rainfall (t) can be determined on the basis of the Montanari formula and time of concentration (τ):

$$t = \frac{n}{1-n} \cdot \tau \quad (\text{Eq. 6})$$

In the Main Project as stated by Pantelić (1965), the duration of relevant rainfall is adopted based on the analysis of the rainfall table in duration t and runoff in duration τ . Three cases are characteristic:

- (1) Duration of rainfall is equal to the duration of runoff ($t=\tau$);
- (2) Duration of rainfall is greater than the duration of runoff ($t>\tau$);
- (3) Duration of rainfall is less than the duration of runoff ($t<\tau$).

In the event that the duration of runoff is less than three days, the duration of relevant rainfall is determined as three days. In the case that the duration of runoff is greater than three days, the duration of relevant rainfall is established to be the same as the duration of runoff. Pantelić (1965) maintains that after analysing consecutive daily precipitation levels, $t=3$ days was for economic reasons adopted as the duration of relevant rainfall. The value of relevant rainfall of 3 days was applied during the calculation of the rate of runoff.

RESULTS AND DISCUSSION

Calculation of the runoff coefficient

Employing the empirical formulas by Nemet and Turazzo, the runoff coefficient and rate of runoff have been determined based on current conditions of the drainage system. In order to reach the most precise runoff coefficient it is necessary to meticulously determine the partial runoff coefficients which are given in the function of terrain slope (α_1), soil permeability (α_2) and vegetation cover (α_3).

Since it is a markedly lowland area, in order to determine the runoff coefficient in the function of terrain slope (α_1), the slope of the Main Canal was used, which steers all water from the analyzed area to the “Galacka” pumping station and has an average slope of 0.005%. Based on the aforementioned, a minimal value of $\alpha_1=0.01$ was adopted from Table 1.

Table 4 represents the estimation of the complex coefficient value α_2 , which was obtained based on the soil type represented in the subject area, as well as their drainage characteristics. To calculate the coefficient in the function of soil permeability (α_2), the percentage share of different soil types was used and values from Table 2 were assigned. The coefficient value in the function of soil permeability which is applied to the entire drainage basin is $\alpha_2=0.21$. The drainage classes of the soils in the subject area are represented in Figure 2.

From the analysis of the CORINE Land Cover 2012 database, which provides soil use and land cover characteristics, a partial coefficient in the function of vegetation cover (α_3) was obtained, with the results displayed in Table 5. Non-irrigated arable land was most represented in the subject area with 62.55%, while natural grasslands were the second most represented with 26.45%. According to the representation of soil types as well as data from Table 3, the value of the coefficient in the function of vegetation cover valid for the entire drainage basin was determined to be $\alpha_3=0.14$. Figure 3 shows the proportion of soils of different land use and type of land cover.

Table 4 Estimating the partial runoff coefficient in the function of soil permeability (α_2)

Soil type	Percentage (%)	Drainage class	α_2	Complex coefficient value α_2
Alluvial waterlogged soil	8.76	II	0.16	0.01401
Carbonate marsh black soil	4.58	II	0.16	0.00734
Brackish carbonate marsh black soil	1.83	I	0.26	0.00476
Marsh black soil without carbonate	33.22	I	0.26	0.08636
Partly brackish marsh black soil without carbonate	1.38	I	0.26	0.00358
Chernozem on sandy loess	0.25	V	0.03	0.00001
Carbonate chernozem (micellar) on a loess terrace	16.38	V	0.03	0.00492
Solonetz	25.28	I	0.26	0.06573
Solonchak-Solonetz	8.32	I	0.26	0.02163
$\Sigma=$	100			0.20834

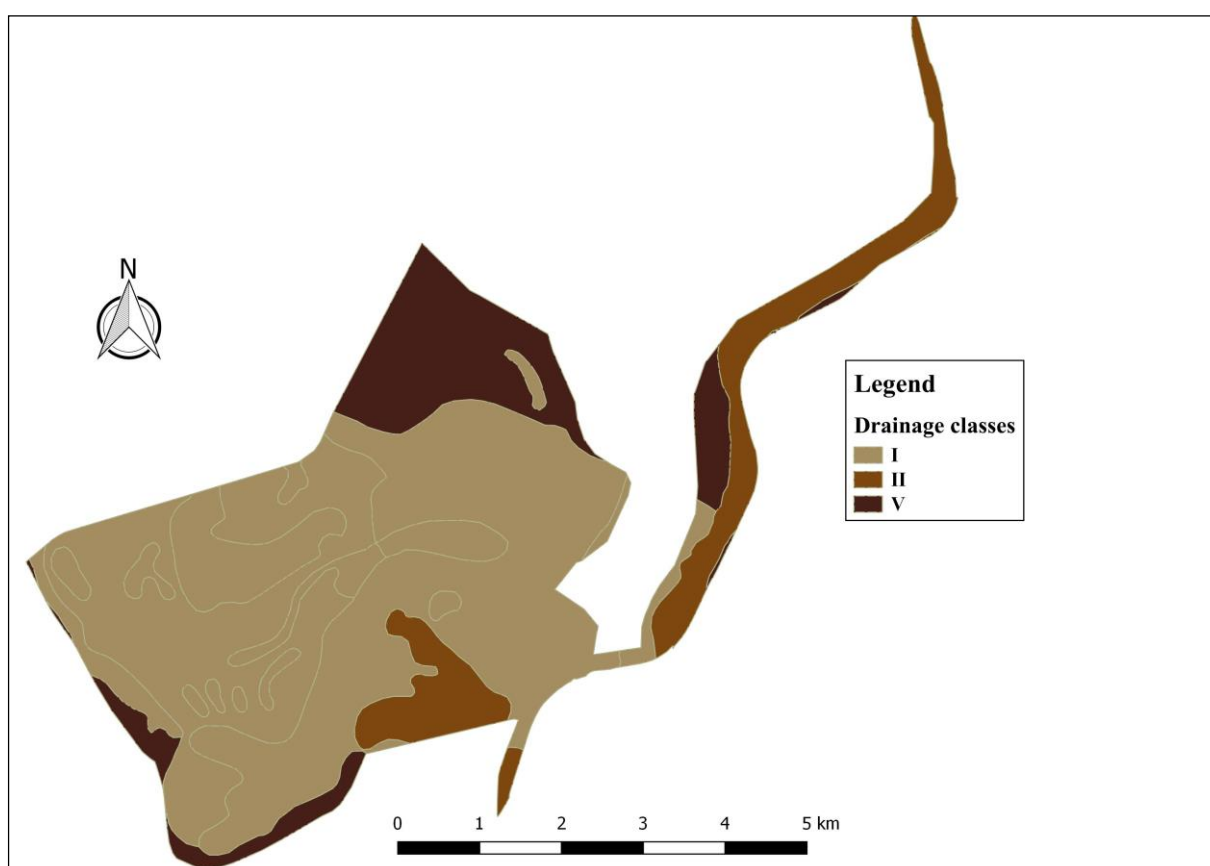


Fig.2 Drainage classes of soil of the Galacka sub-catchment

Table 5 Estimating the partial runoff coefficient in the function of vegetation cover (α_3)

Area description	Percentage (%)	α_3	Complex value of coefficient α_3
Continuous urban fabric	0.01	0.30	0.00003
Non-irrigated arable land	62.55	0.11	0.06881
Pastures	6.11	0.21	0.01282
Complex cultivation patterns	0.89	0.11	0.00098
Predominantly agricultural land with larger areas of natural vegetation	3.43	0.11	0.00377
Natural grasslands	26.45	0.21	0.05554
Inland marshes	0.42	0	0.00000
Mineral extraction sites	0.14	0.3	0.00043
$\Sigma=$	100		0.14238

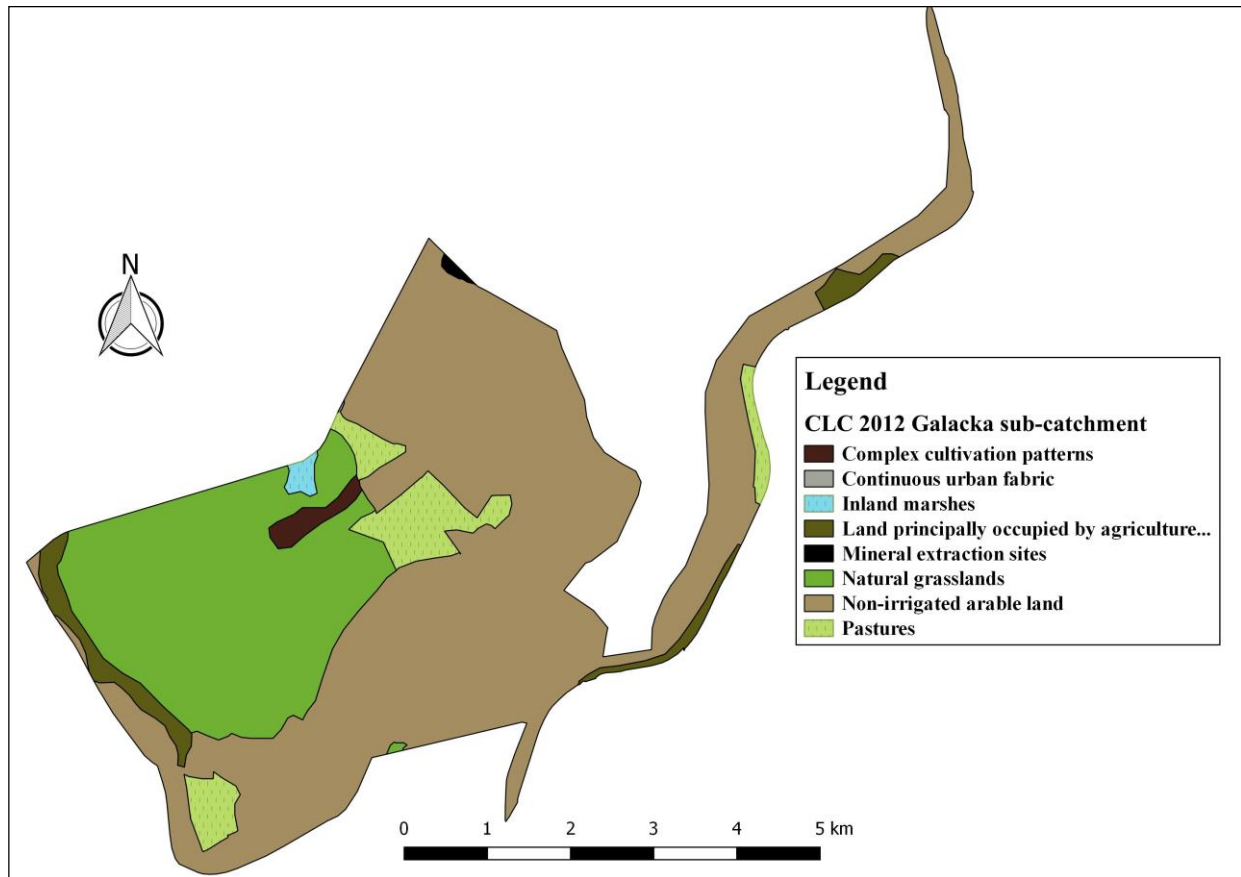


Fig. 3 CORINE Land Cover 2012 map - purpose and characteristics of land cover of Galacka sub-catchment

Implementing the formula (3), the total runoff coefficient of the subject area was assessed as $\alpha=0.36$. The runoff coefficient value calculated for the recent period was slightly greater than the one calculated in the Main Project.

Calculation of the rate of runoff

The time of concentration (τ) for a particular drainage basin from its most distant point to the outlet is determined with the Venturi formula (4) in which the duration of runoff is indicated in the function of the catchment area, with the calculated value being $\tau=1.8$ days.

It is a fact that the duration of the return period takes on an economic character, therefore a return period of 10 years is used in hydromeliorative application during the dimensioning of drainage systems (Belić et al. 1995). Rainfall in a more recent period (1971-2010) was used to calculate the rate of runoff. For that purpose, maximal three-day rainfall in the month of May was used, which occurs once in ten years and amounts to $h=54.7$ mm. Using the formula (2) the maximum rate of runoff was determined to be $q_{max}=0.8 \text{ l s}^{-1} \text{ ha}^{-1}$.

Table 6 displays the comparative results obtained in the 1965 Main Project of the drainage of the Kikinda Canal, Galacka sub-catchment along with the results obtained for the recent period. Considering that the rate of runoff adopted in the Main Project amounts to $q_{max}=0.60 \text{ l s}^{-1} \text{ ha}^{-1}$, while the rate of runoff for the recent period is $q_{max}=0.80 \text{ l s}^{-1} \text{ ha}^{-1}$, we may conclude that they are quite similar.

Table 6 Comparative overview of values from the Project and new values obtained

Parameter	Values from the Project (Pantelić, 1965)	New values	Unit
α_1	0.01	0.01	-
α_2	0.18	0.21	-
α_3	0.11	0.14	-
α	0.30	0.36	-
t	3.00	3.00	days
h	55.4	54.7	mm
q_{max}	0.60	0.80	$\text{l s}^{-1} \text{ ha}^{-1}$

CONCLUSION

With extensive construction carried out on the drainage canal in the middle of the previous century, the soil on the territory of Vojvodina has been transformed from a swamp and marsh area to a soil suitable for agricultural production. The construction of the Kikinda Canal has allowed the drainage of excess water from substantial surfaces of the analyzed area in Banat. The Galacka drainage sub-catchment analyzed in the paper belongs to the system of the Kikinda Canal and the efficacy of its performance has been reviewed.

The biggest differences between the values obtained in the Main Project and those of the analyzed period are

in regard to the size of the runoff coefficient. Sufficient pedological research did not exist at the time of the Project, thus leading to different values of analyzed soil permeability in the more recent study. The coefficient value in the function of soil permeability amounts to 0.18 in the Main Project, while the analysis of more detailed surfaces resulted in a value of 0.21. The utilization of the CORINE Land Cover 2012 database resulted in a partial coefficient in the function of vegetation cover (α_3) for the recent period amounting to 0.14 while that value was 0.11 in the Main Project. The rate of runoff which reflects the current state of the drainage basin ($q_{\max}=0.80 \text{ l s}^{-1} \text{ ha}^{-1}$) is slightly larger than the rate of runoff obtained in the Main Project ($q_{\max}=0.60 \text{ l s}^{-1} \text{ ha}^{-1}$). We may conclude that the constructed system is of satisfactory capacity. The results obtained in this paper are in accordance with the research conducted by Bezdán et al. (2018) on a drainage basin of similar characteristics in another part of Vojvodina (Bačka). According to information received by experts in charge of system maintenance, in the previous period there were no major issues related to drainage of excess water. The problem of retaining smaller amounts of water that remains even after the anticipated drainage deadlines can be solved with the regular maintenance of amelioration canals and the employment of additional ameliorative measures. Onerous water drainage usually occurs on soil of "heavier" mechanical structure, and in such cases, it is recommended to use horizontal pipe drainage or biodrainage (Vranešević et al., 2017).

Based on the obtained results, we can expect adequate performance of the system in place and timely drainage of excess water. It is our recommendation to regularly maintain the system and utilize additional ameliorative measures in order to improve the conditions for agricultural production.

Acknowledgement

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CALIBRATION, VALIDATION AND PERFORMANCE EVALUATION OF SWAT MODEL FOR SEDIMENT YIELD MODELLING IN MEGECH RESERVOIR CATCHMENT, ETHIOPIA

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Abstract

Intensive agricultural practice in Ethiopian highlands results in increasing rates of soil erosion and reservoir sedimentation. The estimation of sediment yield and prediction of the spatial distribution of soil erosion on the upper Megech reservoir catchment enables the local governments and policymakers to maximize the design span life of the Megech reservoir through implementing appropriate soil conservation practices. For this study, the sediment yield was estimated and analyzed through hydrological modeling (SWAT). The simulated outputs of the model show that the mean annual surface runoff was 282 mm and the mean annual streamflow was 153 m³/s. Similarly, 12.33 t/ha mean annual total sediment load gets into the Megech reservoir. The model performance standard used to evaluate the model result indicates that the model was superior in performing the trend of runoff and sediment yield in both calibration and validation periods. Finally, the most erosion vulnerable sub-basins that could have a significant impact on the sediment yield of the reservoir were identified. Based on this, sub-basin 7, 25, 27, 18 and 29 were found to be the most erosion sensitive areas that could have a significant contribution to the increment of sediment yield in the Megech reservoir. Considering the land use, soil type, slope, and relief of erosion vulnerable sub-basins cut off drains, fallow land, contour ploughing, Fanya juu terraces, soil bunds combined with trenches and trees could be the possible management strategies to reduce the sediment yield in the catchment.

Keywords: calibration, validation, Megech Reservoir, sediment yield, SWAT

INTRODUCTION

Sediment yield fluctuates greatly because of natural or man-induced factors. Climate, soil, topography, land use/land cover and management practices are the most common factors that affect the soil erosion process and sediment yield from the catchment. These factors have a dynamic role in the erosional behavior of soil (Wainwright and Brazier, 2011). There are mainly three types of soil erosions namely sheet erosion, rill erosion, and gully erosion. Sheet erosion is the first phase of the erosion process that is characterized by the uniform removal of soil from the surface. As the severity of the erosion increases rill erosion begins to develop and finally deep gully erosion is formed. It is reported that more than 2/3rd of farmland degradation in Africa is caused by soil erosion (Tully et al., 2015). Soil erosion is a natural and dynamic process that occurs when the force of wind, raindrops or runoff on the soil surface exceeds the cohesive agent that binds the soil together (Ifabiyi, 2004). Soil erosion caused by water is a serious problem in many parts of the world which causes most of the degradation of agricultural lands. However, the extent and magnitude varies from one part of the country to another depending on the farming practices, population pressure, type and susceptibility of the soils to erosion, local climate, the general terrain formation, and variations in agroecological setting of the area (Tebebu et al., 2010; Monsieurs et al., 2015). All this implies that location-specific soil erosion studies are still substantial in Ethiopia for arresting the problem of soil loss.

The availability of large amounts of water resources and adequacy of topography enables Ethiopia to be the most beneficiary of water resource development projects such as dams and reservoirs (Setegn et al., 2007). On the contrary poor land use practice and improper management make the reservoirs be in a serious problem of sedimentation even beyond their dead storage capacity. In Ethiopia Poor land-use practices, improper management systems and lack of appropriate soil conservation measures have been major causes of soil erosion and land degradation problems (Tamene et al., 2006). A quantitative expression of soil erosion is a fundamental phase for any watershed management (Prasannakumar et al., 2012; Khadse et al., 2015). Even though different researches (such as Haregeweyn et al., 2017; Gashaw et al., 2018; Miheretu and Yimer, 2018; Woldemariam et al., 2018; Zerihun et al., 2018) have been done so far to estimate soil erosion in the Ethiopia highlands, the problem has been increasing (EfD, 2010) and it could be worse in the future (Niang et al., 2014).

Intensive agricultural practice in the upper Blue Nile basin causes land use to be changed rapidly which results in increased rates of soil erosion and sedimentation. This was manifested by the significant downstream impacts and the storage capacity reduction of reservoirs. Specifically, the silting of reservoirs is the most challenging problem in the upper Blue Nile basin. The benefits gained by the

construction of micro-dams in the upper Blue Nile basins were threatened by the rapid loss of storage volume due to excessive sedimentation (Tamene, 2006). In Megech reservoir catchment the existing land and water resources system of the area is adversely affected by the rapid growth of population, deforestation, surface erosion and sediment transport. Many farmers in the area cultivate mountainous and steeper slope land without protective measures against soil erosion and degradation, causing topsoil to be washed out during the heavy rain season.

The construction of a dam and the creation of an impounded river reach area usually change the stream natural conditions. The dam reservoir causes a reduction in the flow velocity and decreases turbulence thus causing the gradual deposition of those sediments carried by the stream and finally diminishing the reservoir storage capacity. Sedimentation also affects the surface area of the reservoir by reducing water depth and favoring the development of aquatic plant growth. Angerb reservoir constructed in early 1980, to supply water for Gondar town people could not be serving up to the expected design period because of siltation (Admasu, 2005). This implies that the Megech reservoir which is going to be constructed around the same area is expected to face such sedimentation problems. From this experience, it has become a serious concern to determine the trends of streamflow and sedimentation on Megech reservoir catchment for planning, design, and implementation of numerous national water resource development projects in the area.

There is also a knowledge gap concerning the interdependence between the sediment production and watershed treatments on different temporal and spatial scale in the study area. Due to the above reasons, there is a need for hydrological research of Megech reservoir catchment which could support improved catchment management programs to safeguard the alarming degradation of soil and water resources. Since the Megech dam is currently under construction phase, determining the spatial distribution of sediment yield is essential to have efficient reservoir water resource management as per the design life span of the reservoir by improving catchment management practices.

The overall objective of the research was to calibrate, validate and evaluate the performance of the SWAT model for sediment yield modeling and to predict the total sediment load entering to Megech reservoir. The research was also intended to evaluate the spatial distribution of soil erosion for identifying and ranking erosion vulnerable sub-basins of Megech reservoir catchment and to recommend management strategy.

STUDY AREA

Megech reservoir catchment area at the dam site is 394.2 km² which is fully gauged. Megech catchment upstream of the dam site is characterized as a steep mountainous watershed with a relative elevation

difference of 1075 m. The elevation in the catchment has its maximum value in the north-east direction which is 2953 m above mean sea level. The lowest topography land is at the dam site, which is at an altitude of 1878 m above mean sea level. Megech reservoir catchment is presently covered with six types of land covers namely bare land, cultivated land, grassland, shrubland, urban and plantation forest. Cultivated land covers the highest portion of the catchment as it could be seen from the land use map. According to FAO (2002) soil classification system, the major and dominant soil identified in the Megech reservoir catchment are Eutric Leptosols, Eutric Vertisols, Urban, Chromic Luvisols and Haplic Nitosols. As it could be seen from the soil map most of the watershed area is covered with Eutric leptosols. The Megech reservoir catchment area is characterized by severe land degradation situations indicated with excessive soil erosion in the form of sheet, rills, gullies, and land sliding, high deforestation, low vegetation cover, the decline of soil fertility and low land productivity. Gullies are a frequent and permanent phenomenon everywhere, particularly on steep cultivated, grazing and open shrublands. It is evident in almost all slope classes of the catchment area that are kept under cultivation; grazing and open shrublands are exceedingly affected due to soil erosion and land degradation problems. Out of the total study area close to 50% is under this threat.

The climate of the Megech catchment is marked by a rainy season from May to October, with monthly rainfall varying from 67 mm in October to 306 mm in July. The mean annual precipitation is about 1,100 mm in the upper part and about 1,000 mm in the lower part. Rainfall over the Megech catchment is mono-modal with nearly 79 % of the annual rainfall occurring in the period June – September. Maximum temperatures vary from 23 °C in July to 30 °C in March, whereas minimum temperatures range from 11.5 °C in January to 15.6 °C in April & May. Humidity varies between 39% in March and 79% in August. Wind speed is low, thus minimizing potential evapotranspiration values between 101 mm/month in July and 149 mm/month in March (WWDSE, 2008).

The Megech River, which is about 75 km long, has an average annual discharge of 5.6 m³/s. Eighty-five percent of the annual runoff occurs from July to September. The daily minimum river flow record is 4 m³/s whereas the daily maximum river flow is 160 m³/s. The total mean annual sediment load entering the Megech reservoir is estimated as 461,214 t, which corresponds to 1,170 t/km²/year. Megech reservoir capacity is about 182 M m³ of water. The dam is currently under construction phase and it is rock fill embankment type with a crest length of 890 m and height of 76.5m above the river bed level. The dam would allow developing around 7,311 hectares of land using irrigation, besides securing water demand for Gondar town. The dam is provided with side-channel spillway and chute to discharge 662 m³ of water per second without overtopping the dam. The location map of Megech reservoir catchment is shown in Fig. 1.

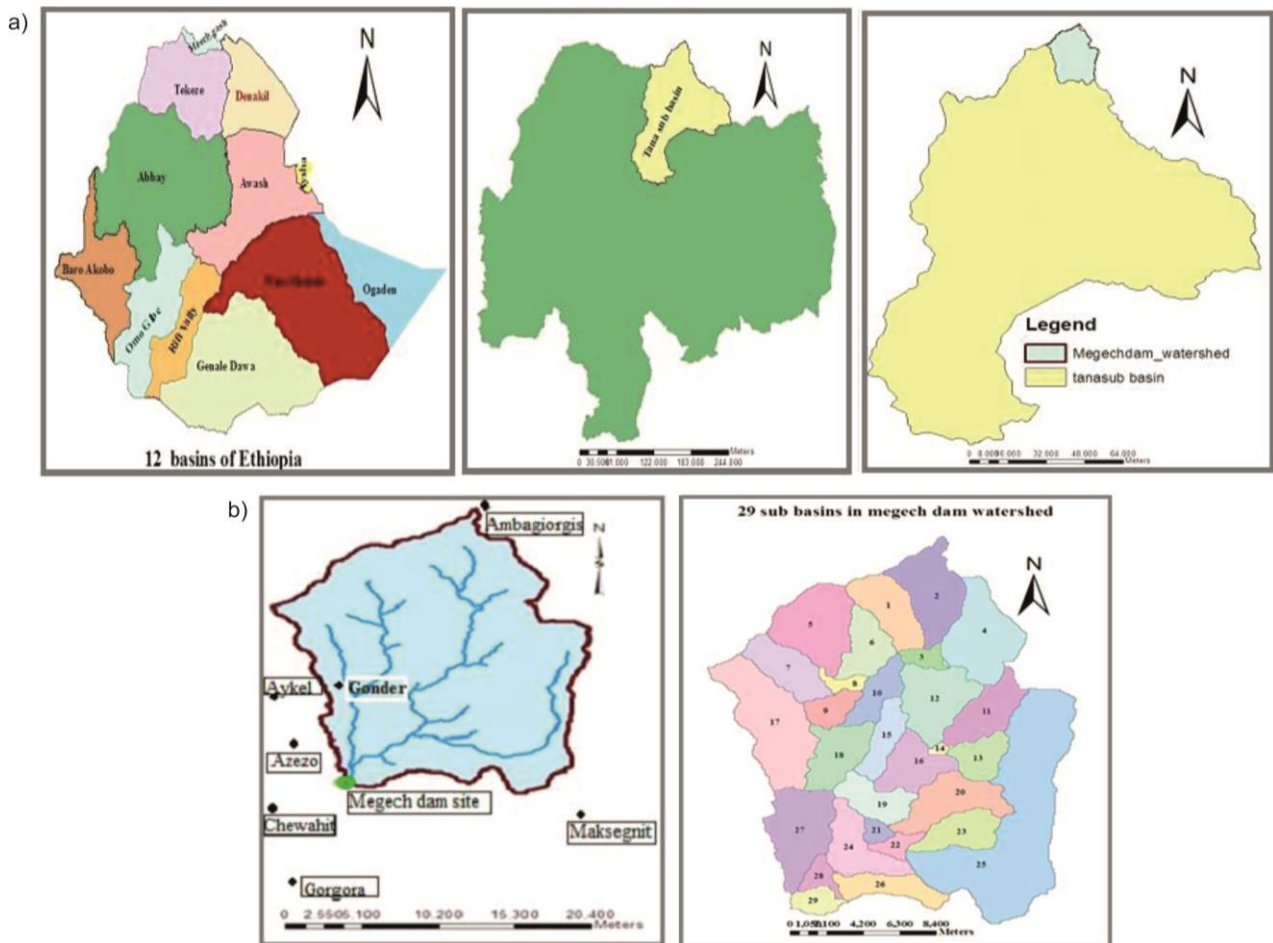


Fig. 1 Location of Megech reservoir catchment in Ethiopia (a) Gauging stations near the study area and the location of the 29 sub-basins in the Megech reservoir catchment (b)

METHODS

There are a wide variety of models used to estimate soil erosion. These models can be physical-based, empirical, and conceptual (Farhan and Nawaiseh, 2015). Arc GIS software and its extension, the Arc SWAT model were used for input data preparation, analysis and modeling purpose of the research. In general, three types of data namely spatial, meteorological and hydrological data were collected for this study. The spatial data (Digital Elevation Map, land use/cover and soil map) have 90m*90m resolution. Fifteen year's daily time series meteorological data (precipitation, air temperature, solar radiation, wind speed, and relative humidity) and hydrological data (streamflow and sediment flow) were also collected starting from Jan 1-2001 to 2015. The data collected were processed until they become an input to the model used. The data processing started by defining all spatial data with the same projection and the watershed delineation. The overlay operation of the land cover map, soil map, and slope map was performed once after the slope classification was made based on the DEM data. Then the hydraulic response unit analysis was done for the spatial input data and the weather/meteorological data table. For the weather generator/ synoptic station all the required values were computed both manually and using helping software

such as WGNmaker4.xlsm and dew02.exe program. Finally, the model was parameterized by converting the results of data analysis into model parameters, then model sensitivity analysis, calibration, validation, and simulation were conducted.

Spatial data collection and analysis

A digital elevation map was collected by the Ministry of Water, Irrigation, and Energy (MoWIE). Flat, undulating plains, rolling plains, Hills and mountainous landforms are the major topographic features of the Megech dam watershed (FAO, 2002). The elevation of the study area ranges from 1878 m to 2953 m a.s.l. The source of land use map shown in Fig. 2 was the Ministry of Agriculture and rural development, a rural land management directorate. Spatial distribution and specific land use parameters were required for modeling. SWAT has predefined land uses identified by four-letter codes and it uses these codes to link land use maps to SWAT land use databases in the GIS interface. Therefore, for the study land uses to be configured by the SWAT lookup table have been prepared and land use types were made compatible with the input needs of the model. Finally, the land uses were reclassified by 4-letter SWAT code and their spatial distribution was prepared. The soil textural and physicochemical properties required by the SWAT model include soil texture, available water

content, hydraulic conductivity, bulk density and organic carbon content for each soil type. These data were obtained from FAO (2002) and the Ministry of Water Resources, Irrigation and Energy. The shape file which describes the distribution of soil in the study area was obtained from the baseline maps available at MoWIE as shown in Fig. 3.

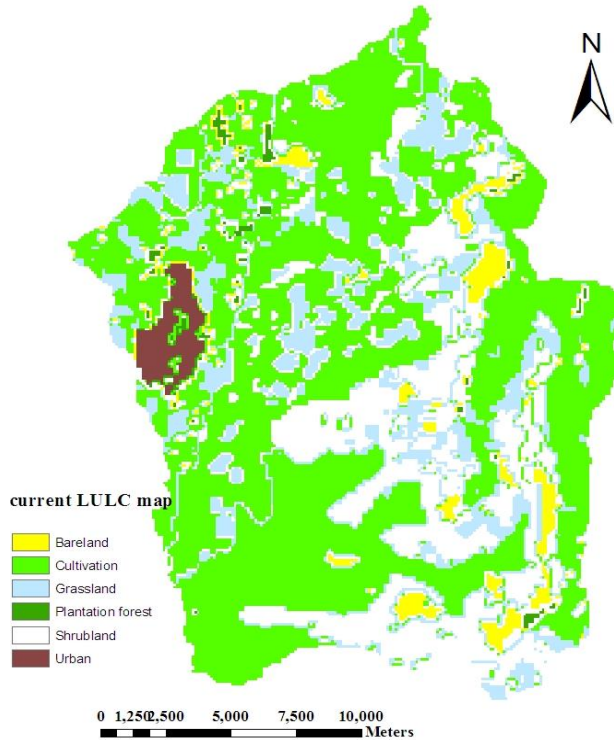


Fig. 2 Land use map of the catchment

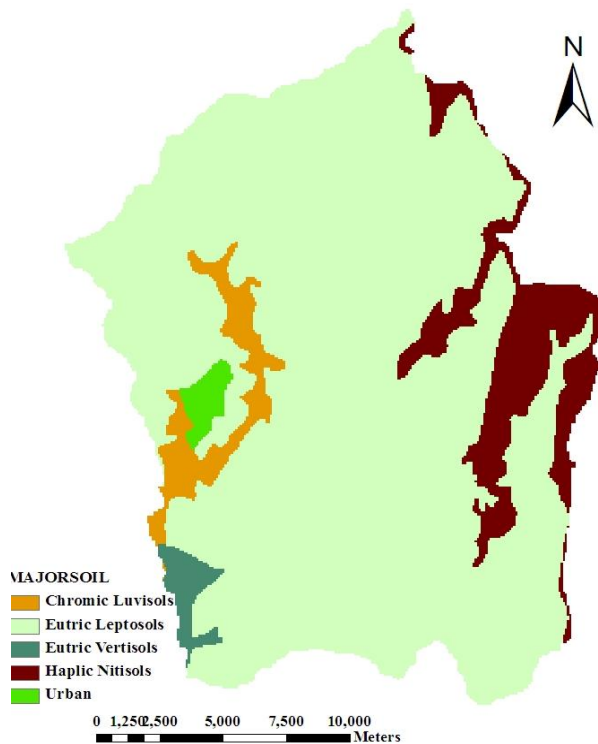


Fig. 3 Soil map of the catchment

Meteorological data collection and analysis

There are six meteorological observation stations within and around the Megech watershed namely Aykel, Gondar, Ambagiorgis, Chewahit, Gorgora, and Maksegnit. For each gauging station, the required daily meteorological data (daily precipitation, daily maximum, and daily minimum air temperature, daily solar radiation, daily wind speed, and daily relative humidity) were collected from the National Meteorological Agency of Ethiopia (NMA) from 2001 to 2015. Checking the availability, quality, consistency, and homogeneity of hydro-meteorological data is imperative for any hydrological model study like SWAT. For this study detail, discussion of both spatial and temporal analysis was made on rainfall, streamflow, and sediment yield. Due to its low impact on the SWAT application, only a simple graphical plot and visual examination was made for the remaining meteorological data.

Rainfall data analysis

Failure of the observer to make the necessary visit to the gage, destruction of recording gages or instrument failure (by mechanical or electrical malfunctioning) may result in missing data. For Hydrological analysis, these missed rainfall data should be first filled with an appropriate method. For this study, missing values were estimated from other stations around the missed record station by using both normal ratio method and simple arithmetic mean method. The normal ratio method was used when the mean monthly rainfall of one or more of the adjacent stations differs from that of the missed record station by more than 10%. Whereas, the simple arithmetic mean method was used when the mean monthly rainfall of all the adjacent stations is within 10% of the station under consideration. Homogeneity of the selected rainfall stations had been checked by using Non-dimensional values of the monthly precipitation. The homogeneity test plot shows that all of the rainfall stations used for this particular study were homogenous and their rainfall pattern was found to be monomodal with high rainfall season from July to September and low rainfall season from February to March. In this study double mass curve, spatial consistency test method is used to check the consistency of rainfall data for the research period.

The spatial analyses of rainfall for all gauging stations were made for the research period (2001-2015) and its result is located in Fig 4. As could be seen from the graph comparisons of the two principal stations were made and Gonder station was found to be the best representative of the catchment than Aykel. Hence, using Gonder station as a weather generator provides better output than using Aykel. Rain gauges represent point sampling of the areal distribution of a storm. In practice, hydrological analysis requires knowledge of the rainfall over an area. Due to its simplicity, the Thiessen polygon method is used to calculate areal rainfall and is given by:

$$P_{ave} = \sum_{i=1}^n \left(\frac{P_i * A_i}{A_t} \right)$$

where P_{ave} is average areal rainfall (mm), $P_1, P_2, P_3, \dots, P_n$ is precipitation of station 1, 2, 3...n, respectively and $A_1, A_2, A_3, \dots, A_n$ is area coverage of station 1, 2, 3...n respectively in the Thiessen polygon.

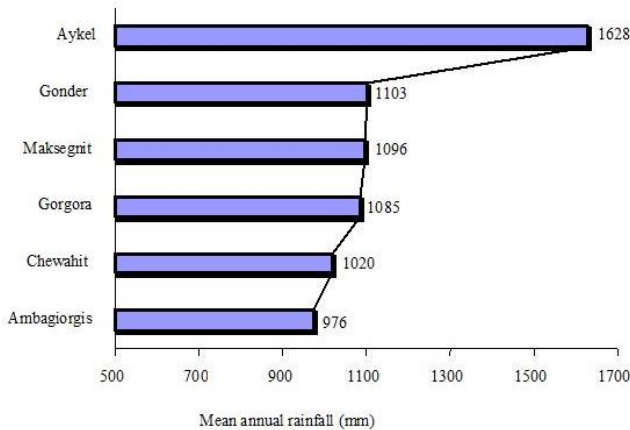


Fig. 4 Mean annual rainfall of stations in the catchment (2001–2015)

Hydrological data collection and analysis

Both the daily streamflow and sediment data were collected from the Ministry of Water, Irrigation, and Energy (MoWIE), from 2001 to 2015 (starting on Jan 1-2001) at Azezo gauging station. Unlike streamflow data, sediment data records exhibit several jumps. Due to the lack of continuous-time step suspended sediment records, the sediment rating curve was developed for this particular study by using the measured sediment records as a function of the corresponding streamflow values. The sediment rating curve is a widely applicable technique for estimating the suspended sediment load being transported by a river through signifying a relationship between the stream discharge and sediment concentration or load (Clarke, 1994).

The general relationship of suspended sediment rating curve can be written as:

$$Q_s = a * Q^b$$

where: Q_s is sediment load in t/day, Q is the stream discharge in m^3/s and a & b are regression constants. To work on the above formula the first task was the conversion of the measured suspended sediment concentration (mg/l) records that were collected from the MoWIE into sediment load (t/day) by using the following conversion formula:

$$S = 0.0864 * Q * C$$

where: S is sediment load in (t/day), Q is streamflow (m^3/s), C is sediment concentration (mg/l) and 0.0864 is conversion factor.

$$Q_s = 28.46 * Q^{1.213}$$

where: Q is streamflow (m^3/s) and Q_s suspended sediment load (t/day). The relationship is known as the suspended sediment rating curve and is shown in Fig. 5.

SWAT simulation is based on the total sediment load (suspended + bed load). However, there was no measured data on bedload material. Hence considering the mountainous nature of Megech River it was decided that the bedload for the Megech catchment would be estimated as being 10% of the suspended load (WWDS, 2008).

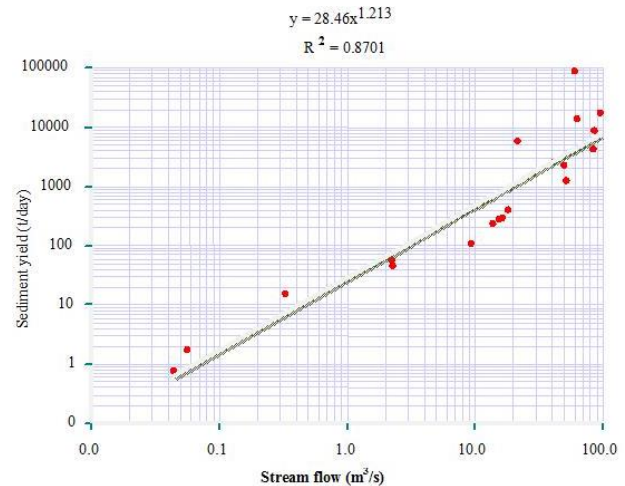


Fig. 5 Sediment rating curve of Megech River (Nr. Azezo)

SWAT model set up

The Megech reservoir catchment modeling was done by the SWAT model that is compiled using the AVSWATX interface (ArcView GIS interface for SWAT). The first step in the SWAT model setup was watershed delineation and stream network determination (Neitsch et al. 2009) using the Megech reservoir catchment DEM and taking the center of the Megech dam axis at the river bed level as an outlet point. Next, the study catchment was divided into sub-watersheds based on the concept of flow direction and accumulation; and sub-watersheds were further subdivided into smallest unit called hydraulic response units which consist of unique combinations of homogeneous soil, land use properties, and slope range (Arnold et al., 2012). The runoff and sediment yield is estimated separately for each hydraulic response unit and routed to obtain the total value for the watershed (Winchell et al., 2007). Finally, weather data definition and simulation were followed by sensitivity analysis and calibration.

Sensitivity analysis, calibration, and validation

The default simulation output in the SWAT model run can not be directly used for further analysis. Instead, the ability of the model to sufficiently predict the constituent streamflow and sediment yield should be evaluated through sensitivity analysis, model calibration, and validation (White, 1992). Performing the calibration process for all model parameters becomes complex and computationally far-reaching. In such cases, sensitivity analysis is helpful to identify and rank parameters that have a significant impact on specific model outputs of interest. The flow and sediment parameters considered by the model for sensitivity analysis are shown in Table 1 and Table 2 respectively. The sensitivity analysis method implemented in the SWAT model is called the Latin Hypercube One-At-a-Time (LH-OAT) design (van Griensven and Srinivasan,

2005). After running sensitivity analysis, the sensitive parameters were categorized into four classes based on their mean relative sensitivity (MRS). The four classes are Small to negligible ($0 \leq \text{MRS} < 0.05$), Medium ($0.05 \leq \text{MRS} < 0.2$), High ($0.2 \leq \text{MRS} < 1$) and Very high ($\text{MRS} \geq 1$) (Lenhart et al., 2002). Based on this classification, both flow and sediment parameters with mean relative sensitivity value of medium to very high had been selected for calibration.

For this study, the sensitivity analysis was performed from January 1, 2003, to December 31, 2009, in which the first two years (2001 and 2002) were taken as warm-up periods. Model calibration is the modification of parameter values and comparison of predicted output of interest to measured data until a defined objective function is achieved (James and Burges, 1982). Calibration of streamflow and sediment yield was carried out at the outlet of sub-basin 29 (near Azezo gauging station). Model validation is testing of calibrated model results with independent data set without any further adjustment (Neitsch, 2005) at different spatial and temporal scales. Table 3 shows both the calibration and validation periods.

Table 3 Calibration and validation periods for flow and sediment

Types of Simulation	Period of Simulation
flow calibration	2001 - 2009
flow validation	2010 - 2015
Sediment calibration	2001 - 2009
Sediment validation	2010 - 2015

Performance evaluation of the SWAT model

Three methods for performance evaluation of model predictions were used during the calibration and validation periods namely Regression coefficient (R^2), Nash and Sutcliffe simulation efficiency (ENS) and Relative Volume Error (RVE). R^2 value greater than 0.6 is acceptable (Santhi et al., 2001) and its value can be calculated by the following equation:

$$R^2 = \frac{\left[\sum_{i=1}^n (q_{si} - q_s)(q_{oi} - q_o) \right]^2}{\sum_{i=1}^n (q_{si} - q_s)^2 \sum_{i=1}^n (q_{oi} - q_o)^2}$$

Table 1 Flow parameters for sensitivity analysis

Flow parameters used for sensitivity analysis	unit	SWAT_code
Alpha base flow recession constant	day	Alpha_Bf
Threshold depth of water required for return flow to occur	mm	Gwqmn
Initial SCS CN II value	%	Cn2
Soil evaporation compensation factor	–	Esco
Effective Channel Hydraulic Conductivity	mm/hr	Ch_K2
Available water capacity	mm water/mm soil	Sol_Awc
Threshold depth of water required for evaporation to occur	mm	Revapmn
Soil depth	mm	Sol_Z
Maximum Potential Leaf Area Index	–	Blai
Maximum Canopy Index	mm	Canmx
Groundwater evaporation coefficient	–	Gw_Revap
Soil conductivity	mm/hr	Sol_K
Ground water delay	day	Gw_Delay
Average slope steepness	m/m	Slope
Manning coefficient for channel	–	Ch_N2
Plant evaporation compensation factor	–	Epc
Surface runoff lag coefficient	–	Surlag
Soil Albedo	–	Sol_Alb

Table 2 Sediment parameters for sensitivity analysis

Sediment parameters used for sensitivity analysis	unit	SWAT_code
USLE support Practice factor	–	Usle_P
Average slope steepness	m/m	Slope
Linear factor for channel sediment routing	–	Spon
Available water capacity	mmH2O /mm soil	Sol_Awc
Soil Albedo	–	Sol_Alb
Exponential factor for sediment routing	–	Spexp
Soil conductivity	mm/hr	Sol_K
Maximum Potential Leaf Area Index	–	Biomix
Channel Cover factor	–	Ch_Cov
Channel Erodibility factor	–	Ch_Erod
USLE cover factor	–	Usle_C

Where: q_{si} is the simulated values of the quantity in each model time step, q_{oi} is the measured values of the quantity in each model time step, q_s is the average simulated value of the quantity in each model time step, q_o is the average measured value of the quantity in each model time step.

ENS value greater than 0.5 is acceptable (Nash and Sutcliffe, 1970) and its value can be calculated as follows:

$$ENS = 1 - \frac{\sum_{i=1}^n (q_{oi} - q_{si})^2}{\sum_{i=1}^n (q_{oi} - q_o)^2}$$

Where: q_{si} is the simulated values of the quantity in each model time step, and q_{oi} is the measured values of the quantity in each model time step and q_o is the average measured value of the quantity in each model time step.

A relative volume error of less than +5 % or -5% indicates that a model performs well while relative volume errors between +5% and +10% and -5% and -10 % indicate a model with reasonable performance.

$$RVE = \frac{\sum (Q_{sim} - Q_{obs})}{\sum Q_{obs}} * 100\%$$

where RVE is relative volume error in %, Q_{sim} is simulated discharge and Q_{obs} is observed discharge in each model time step.

RESULTS AND DISCUSSION

Stream flow modeling

Eight flow parameters with a sensitivity class of very high to medium were selected for calibration as listed in Table 4. The simulated mean annual streamflow after calibration shows a good agreement with the observed data set as indicated in Fig. 6. Even though the pattern agreement was good for simulated and calibrated model the streamflow volume error was found to be -8.64 during the calibration period. The possible causes can be inefficient manual calibration, incorrect rainfall and streamflow record, error in estimating missed flow and precipitation data. $R^2 = 0.71$ and $ENS = 0.63$ were calculated.

During the validation period (2010-2015) the performance of the model was evaluated and gives a value of $R^2 = 0.79$ and $ENS = 0.83$. Even though the relative volume error is somewhat large the (R^2) and (ENS) value lies in the acceptable range, hence it is possible to say that the SWAT model was successful to simulate realistic flow with a little deviation from observed streamflow for this particular research as shown in Fig. 7.

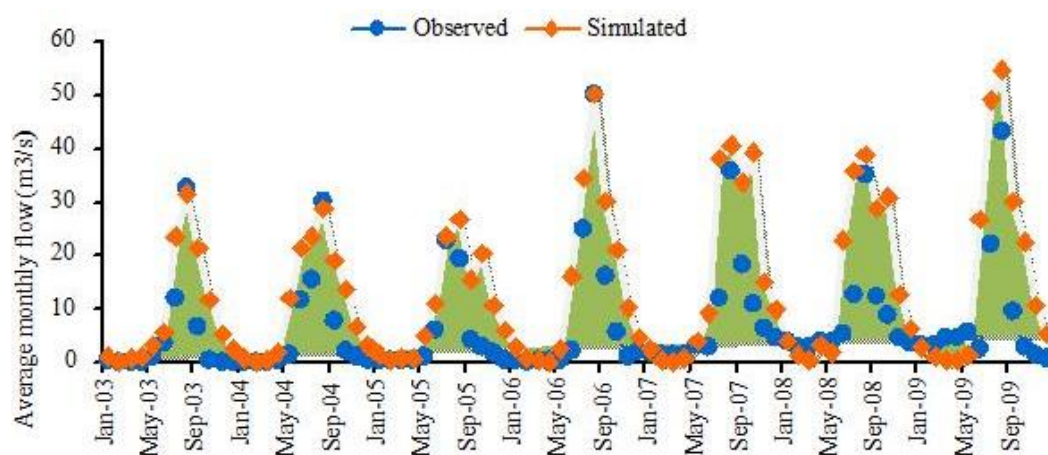


Fig. 6 Observed and simulated streamflow for the calibration period (2003-2009)

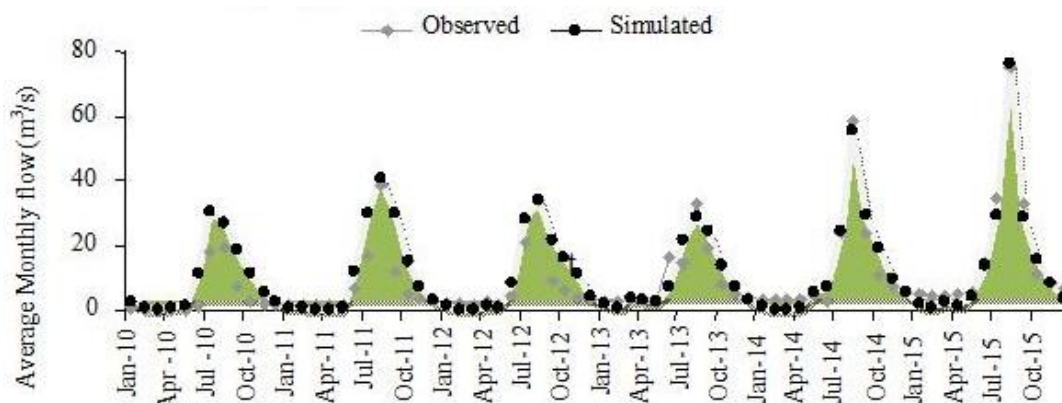


Fig. 7 Observed and simulated streamflow for the validation period (2010-2015)

Table 4 Calibrated values of sensitive flow parameters

Rank	Flow parameters	Sensitivity index (MRS)	Class of sensitivity	Allowable range of calibration	Calibrated values
1	Alpha_Bf	1.39E+00	very high	0-1	0.091
2	Gwqmn	2.56E-01	high	0-1000	360
3	Cn2	9.46E-02	medium	±25	11
4	Esco	9.22E-02	medium	0-1	0.91
5	Ch_K2	5.32E-02	medium	0-1	0.71
6	Sol_Awc	5.25E-02	medium	±25	5.8
7	Revapmn	5.24E-02	medium	0-1000	291
8	Sol_Z	5.10E-02	medium	±25	21

Sediment yield modeling

Six sediment parameters with a sensitivity class of very high to the medium were selected for calibration as listed in Table 5. Unlike streamflow simulation, the mismatch gap between measured and simulated sediment yield was found to be large for default simulation. The possible cause for this variation might be the lack of enough measured sediment data used during sediment rating curve development as most of the sediment samples were not representatives of the whole simulation periods. The sediment yield was initially calibrated manually for mean annual conditions until the simulated output coincides with the measured sediment load (t/ha/year).

Next to mean annual sediment yield calibration the monthly time step calibration was carried out by varying sediment sensitive parameters iteratively within the allowable ranges until a satisfactory agreement between observed and simulated sediment yield was obtained. Lastly monthly time step sediment yield hydrograph was developed to compare the observed and simulated sediment load values for the calibration period. The comparison between observed and simulated sediment flow for the calibration period was shown in Fig. 8.

Disparate from calibration, the sediment yield hydrograph of measured and simulated output during the validation period shows a good agreement. This was mainly due to the availability of enough measured sediment samples taken during the validation period which later used for sediment rating curve preparation. This ensures that the observed sediment load data used for model input during the validation period were more representative and better approach to reality than the calibration period. The comparison between observed and simulated sediment flow for the validation period was shown in Fig. 9. Finally, measures of model performance values for sediment were summarized in Table 6. The model performance standard used to evaluate the model result indicates that the model was superior in performing the trend of runoff and sediment yield in both calibration and validation periods.

Table 5 Calibrated values of sensitive sediment parameters

Rank	Sediment parameters	Sensitivity index (MRS)	Class of sensitivity	Allowable range of calibration	Calibrated values
1	Usle_P	2.71E+00	very high	0-1	0.81
2	Slope	1.01E+00	very high	±25	6.1
3	Spcon	4.86E-01	high	0.0001-0.01	0.0041
4	Sol_Awc	3.11E-01	high	±25	15.3
5	Sol_Alb	5.62E-02	medium	±25	-3
6	Spexp	5.26E-02	medium	1-2	1.43

Table 6 Measures of model performance for sediment

Parameters	Calibration (2003-2009)	Validation (2010-2015)
R ²	0.82	0.9
ENS	0.77	0.81

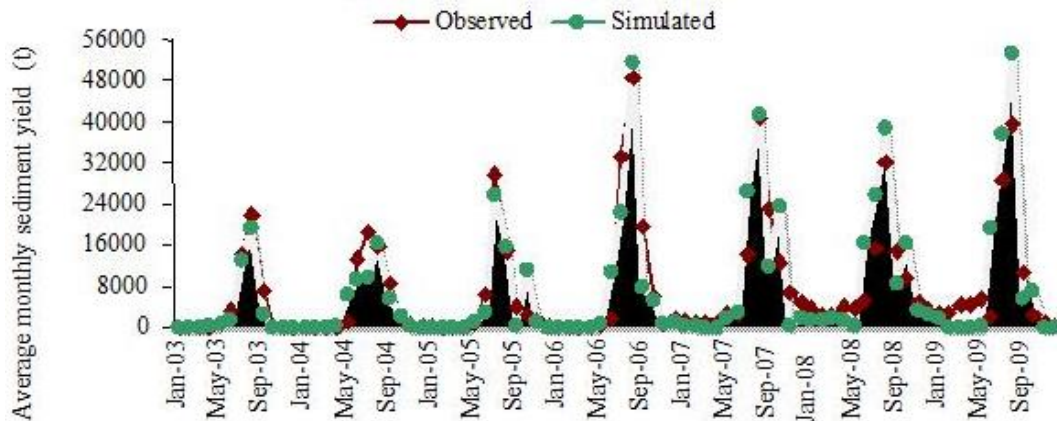


Fig. 8 Observed and simulated sediment flow for calibration period (2003–2009)

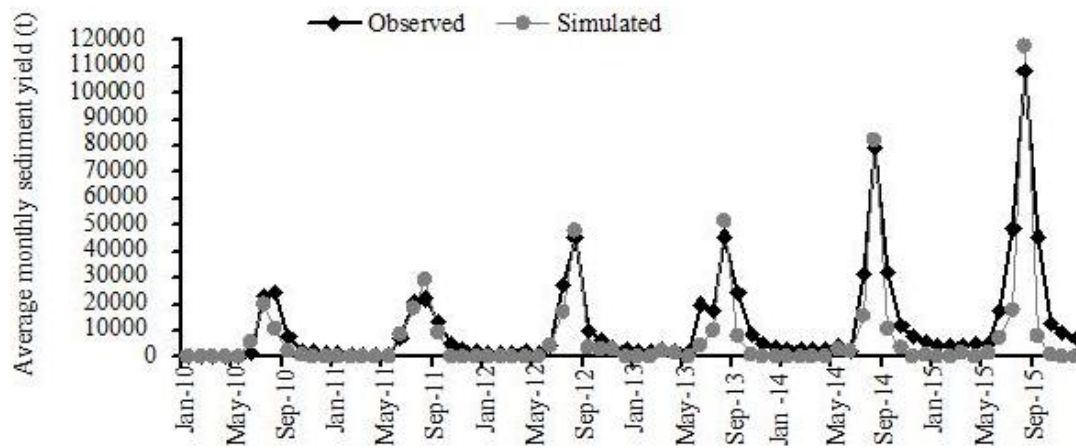


Fig. 9 Observed and simulated sediment flow for the validation period (2010-2015)

Spatial model responses to runoff and soil loss

Once sensitivity analysis, calibration, and validation of the model was done for both streamflow and sediment yield the next step was to simulate the model for the whole period of research baseline (2001-2015) and quantify the model response to runoff and soil loss as shown in Table 7. The catchment was subdivided into 29 sub-basins as shown in the location map. The erosion risk map was developed depending on the severity classes adopted from Haregeweyn et al. (2017). Based on Haregeweyn et al. (2017) recommendation the soil loss (t/ha/year) < 5 was very slight, 5-15 slight, 15-30 moderate, 30-50 severe and > 50 was very severe. The map showed that 33.25 % and 66.75 % of the catchment area was experienced slight and moderate soil erosion rate respectively. On average 12.33 t/ha mean annual sediment load gets into the Megech reservoir. The overall spatial distribution of the soil erosion on the catchment was summarized in Table 8. Sub-basin 7, 25, 27, 18 and 29 contribute the highest mean annual sediment load to the Megech reservoir and are identified as the most erosion vulnerable sub-basins of the Megech reservoir with 17.8, 16.86, 15.97, 15.91 and 15.74 t/ha/year soil losses respectively.

Table 7 Model response to runoff and soil erosion

Runoff (mm)	Sediment yield (t/ha)	Base flow (mm)	Total water yield (mm)
282	12.33	504	786

The land use/land cover map shows that the catchment is covered by 64.34 % of cultivated land, 1.19 % of plantation forest, 7.8 % of grassland, 20.59 % of shrubland, 2.95 % of bare land and 3.14 % of urban. Most of the erosion of vulnerable sub-basins are covered with cultivated/agricultural land uses. An agricultural land is exposed to pulverization of the soil during the frequent tillage practice in the study area and increases the erosion rate as it could be seen in the field visit. The soil map shows that the catchment is covered by 84.35% Eutric Leptosols, 9.47% Haplic Nitisols, 3.77% Chromic Luvisols, 1.04 Urban and 1.38% Eutric Vertisols.

Table 8 Spatial distribution of sediment yield in Megech reservoir catchment

Sub-basins	Area (ha)	Mean annual surface runoff (mm)	Mean annual soil loss (t)	Sediment yield (t/ha)	Rank
1	1419.8	233	14,354	10.11	23
2	1889.9	230	18,710	9.9	23
3	324.04	204	2,262	6.98	28
4	2272.4	207	25,224	11.1	22
5	2178.1	235	18,100	8.31	25
6	1109.1	221	10,159	9.16	24
7	1292	301	22,998	17.8	1
8	262.24	271	2,145	8.18	26
9	613.84	352	7,992	13.02	14
10	861.88	303	12,825	14.88	8
11	1307.8	216	15,471	11.83	19
12	1870.7	185	25,086	13.41	10
13	837.66	315	9,809	11.71	20
14	90.197	236	1,341	14.87	9
15	901.13	261	11,904	13.21	12
16	1216.8	253	8,652	7.11	27
17	3091.7	390	39,110	12.65	16
18	1332.1	262	21,194	15.91	4
19	1038.1	387	16,070	15.48	6
20	1631.1	271	21,824	13.38	11
21	238.85	328	3,580	14.99	7
22	345.75	311	4,522	13.08	13
23	1090.7	290	12,118	11.11	21
24	1393.9	327	17,717	12.71	15
25	6925.9	390	116,771	16.86	2
26	983.81	250	6,306	6.41	29
27	2047.8	322	32,703	15.97	3
28	379.16	296	4,489	11.84	18
29	472.7	331	7,440	15.74	5
Average basin value:		282	17,616	12.33	

Eutric Leptosols are the dominant soil type in these areas as it could be seen in the soil map of the study area and the relief is hills type, which could be also another reason for the increments of soil erosion. Considering the above land use, soil type, slope, and relief of erosion vulnerable sub-basins cut off drains, fallow land, contour ploughing, Fanya juu terraces, soil bunds combined with trenches and trees could be the possible management strategies to reduce the sediment yield in the catchment.

CONCLUSIONS

As per the objective of this particular research the spatial distribution of sediment yield was estimated and erosion vulnerable sub-basins were ranked and analyzed statistically by using a semi-distributed model called SWAT. The model performance criterion used to evaluate the model result indicates that the model was superior in performing the trend of sediment yield in both calibration and validation periods. The simulated output of the model shows that 12.33 t/ha/year sediment load gets into the Megech reservoir. But, Megech Dam design report shows as the dead storage capacity of the dam was designed by considering 11.7 t/ha/year sedimentation rates. Hence, the designers are recommended to revise the dead storage capacity of the reservoir to include the incremental rate of sedimentation. Beside this local governments and policymakers are highly recommended to implement appropriate management strategies such as cut off drains, fallow land, contour ploughing, Fanya juu terraces, soil bunds combined with trenches and trees on that erosion vulnerable sub-basins to maximize the design span life of the Megech reservoir through reducing the sediment yield generated from the catchment.

The major limitation during this research work was lack of bedload data and continuous measured suspended sediment data. Only a few sediment concentration measurements were available during different years. The best option for this problem was to generate the daily sediment data from sediment rating curves developed by using available measurements. Therefore, to get better-simulated sediment output that approaches the actual measured data responsible bodies are recommended to record frequent and reliable sediment data.

Finally, this study does not consider a scenario changes to compare the corresponding changes in streamflow and sediment yield. But, different variables such as land use land cover changes, climate changes, and management activities might have a significant impact on streamflow and sediment yield of the research area. Hence, future researchers are highly recommended to consider these variables for estimating the corresponding impacts on streamflow and sediment yield.

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CHARACTERISTICS OF POST SOCIALIST SPATIAL DEVELOPMENT OF THE FUNCTIONAL URBAN AREA OF VESZPRÉM, HUNGARY

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Abstract

The post-socialist era resulted remarkable changes in urban landscape in Eastern Europe and in Hungary. The special circumstances caused moderate level of urbanisation and special patterns of urban sprawl, traceable in land use changes. The urban sprawl and suburbanisation became an important trend around smaller Hungarian cities as well. Regulators are eager to rule the evolution of spaces, however, it is hard to control all aspects of land use. The research presented in this paper shows the dynamics of new artificial areas with the help of land use changes from the Corine Database for the functional urban area around Veszprém and attempts to find the most important policy responses to the growing artificial surfaces after transition. The research questions are: What are the most important trends in changing in-built areas in a small city after the transition? What kind of new artificial areas appeared and where are they situated? Were the land use plans and nature protection effective tools for manage urban sprawl? With the help of Corine land use changes between 1990-2018 the most important spatial changes are shown, and the different peri-urban areas are compared around the core town. Attention is drawn to the importance of regulation for sustainable land use and protection of resources. It also highlights the importance of the regulatory power of municipalities. Changes in the environment of Veszprém may give inspiration for the rethinking the relationship of urban-rural, and catchment area and core town.

Keywords: land use analyses, urban sprawl, Veszprém, post-socialist urban development, regulation

INTRODUCTION

One of the commonly mentioned challenges of the future is urban sprawl (EEA, 2016) and land use as the essential factor of it (ESPON, 2006; EEA, 2007). There is also a growing body of literature that recognizes the importance of the most influenced territories: role of the central city and its settlement network, the periphery, edge, peri urban territories (Meeus and Gulinck, 2008; Csemez, 2008; Piorr et al., 2011; Szirmai, 2011; Woltjer, 2014; Oueslati, 2015). The spatial context of urban sprawl is also highlighted and researched by international bodies like OECD and the EU and the definitions of functional urban area (FUA) (OECD, 2012) or settlement group municipalities (KSH, 2014) are integrated into the international and national statistical systems as well. Studies also attempt to find regulatory or other assets to control or manage the growth of urban areas (Allen, 2003; Ros-Tonen, 2015; Geneletti et al., 2017) and suggests sustainable development, the management of urban sprawl and its consequences and also foster the densification of artificial surfaces (Artmann et al., 2019).

The special aspects of urban development in Eastern Europe – the semi-peripheral situation, the slow transition of society based on agricultural to industrial production, the changing regulatory system after socialism, postponed urbanisation process during socialism, and despite of intensive suburbanization after 1990, a moderate level of urbanisation (Enyedi, 1988; Beluszky and Györi, 2005; Enyedi, 2012;) – give additional motivation to researchers

and planners to highlight the causes and the possibilities to cope with urban sprawl. Several studies focus on the importance of land use changes of cities and towns as well in post socialist countries (for example Lincaru et al., 2016; Grigorescu and Kucsicsa, 2017 in Romania; Roose et al., 2013 in Estonia; Slaev and Kovachev, 2014 in Bulgaria; Zivanovic-Miljkovic et al., 2012 in Serbia) and most of them urges the importance of regulatory tools to manage land use changes in peri-urban areas.

Hungary is also affected by increase of artificial areas, however in several regions the population of urban fabric decreases (Hennig et al., 2015). Several researches showed the tendencies and differences within Hungary (for example Ladányi and Szelényi, 1997; Bajmócy, 2001; Timár, 2005) as well as in small cities like Győr, Pécs, Miskolc (Lux, 2014, Hardi, 2012; Somlyódyne Pfeil, 2012), Szeged (Mucsi, 2011), Kecskemét (Ricz et al., 2009), Nyíregyháza (Kókai, 2006), most of all focus on socio-economic changes and consequences, but not land use changes. Although the trends are well known, the Hungarian spatial planning could not find satisfactory answer to manage urban sprawl and negative tendencies of increasing land consumption.

In our research we explore the trends of spatial growth of a smaller Hungarian town, Veszprém and its functional urban area. In spite of the fact that the importance of agglomeration is highlighted in towns with more than 100 000 inhabitants in literature, the agglomerational potential of the town is underlined. With its almost 60 000 inhabitants it has regional importance in the Transdanubian

region of Hungary (Koós, 2010; Hardi, 2015), but no such case study focusing on Veszprém and its surroundings has been published yet. Our research area was delineated into 3 characteristic parts: an outer fringe, an inner fringe and the core town according to the international and also broader delineation of catchment settlements - FUA, and the national, more focused agglomeration arena - settlement groups. Land use changes were analysed based on Corine Database between 1990 and 2018, in 4 periods. Results were also compared to the former land use management plans on country and on municipality level (in the case of Veszprém).

STUDY AREA

The area at the Central-Transdanubian region in Hungary (Fig. 1), along the Lake Balaton highlands and Bakony mountain has diverse natural and landscape features: topography, natural environment is characteristic and protected. The temperate climate is mild, becomes warmer closer to the Lake Balaton (Balaton-Riviera). The annual precipitation varies between 500-800 mm. Sedimentary and volcanic aquifers are both found in the fragmented landscape. In addition to the diverse natural values of the area it is also an important cultural landscape. In addition to management based on landscape characteristics (vineyards or cultivation of herbs) its ethnological values are unique (Dövényi, 2010). The land use patterns are also diverse here. Several settlements have agricultural or forestry tradition (Szentgál, Zirc) however, industrialisation also caused significant changes (Balatonfüzfő, Papkeszi). In addition, a military training field is also located here, with regular international exercises. As the area partly belongs to the preferred holiday destination and is a popular target of investments in recent years, it's natural values and landscape

management are threatened. Therefore, developments are particularly important in accordance with the outstanding landscape system and values.

The centre of the study area is Veszprém town, which is approx. 12 690 ha and a specific topographic location thanks to the vicinity of lake Balaton, foot of Bakony mountain and Séd creek. It is the pole town of its surrounding FUA (131 310 ha) and also its settlement group (53 932 ha). The town's former administrative and educational character has changed. New technical university was founded, and several industrial sites were opened, the population grew from about 20 500 (1949) to about 63 000 (1990) during the socialist era. Now Veszprém has almost 60 000 (2018) inhabitants (teir.hu). The transition brought a less intensive development, but today Veszprém is an economical focus point of Western Hungary thanks to several companies, which have chosen Veszprém as new location.

METHODS

In our study the administrative area of Veszprém and its surrounding – the settlement group (defined by KSH, 2014) and functional urban area (FUA) (based on the Urban Atlas 2012) were analysed (Fig.1). Using the Corine land use maps (CLC changes layer) from 1990-2000, 2000-2006, 2006-2012 and 2012-2018 the land use changes have been calculated and visualized for the study area in Geographical Information Systems (GIS) – ArcMap software 10.2.2. The categories defined on the basis of Corine nomenclature (Table 1) show the trend of the change. If the changes stayed within the category of three main land use pattern (artificial, agricultural and natural) it was identified as unchanged and was not highlighted during the analyses. However, the scale of the Urban Atlas would mean a better basis for analyses, it is

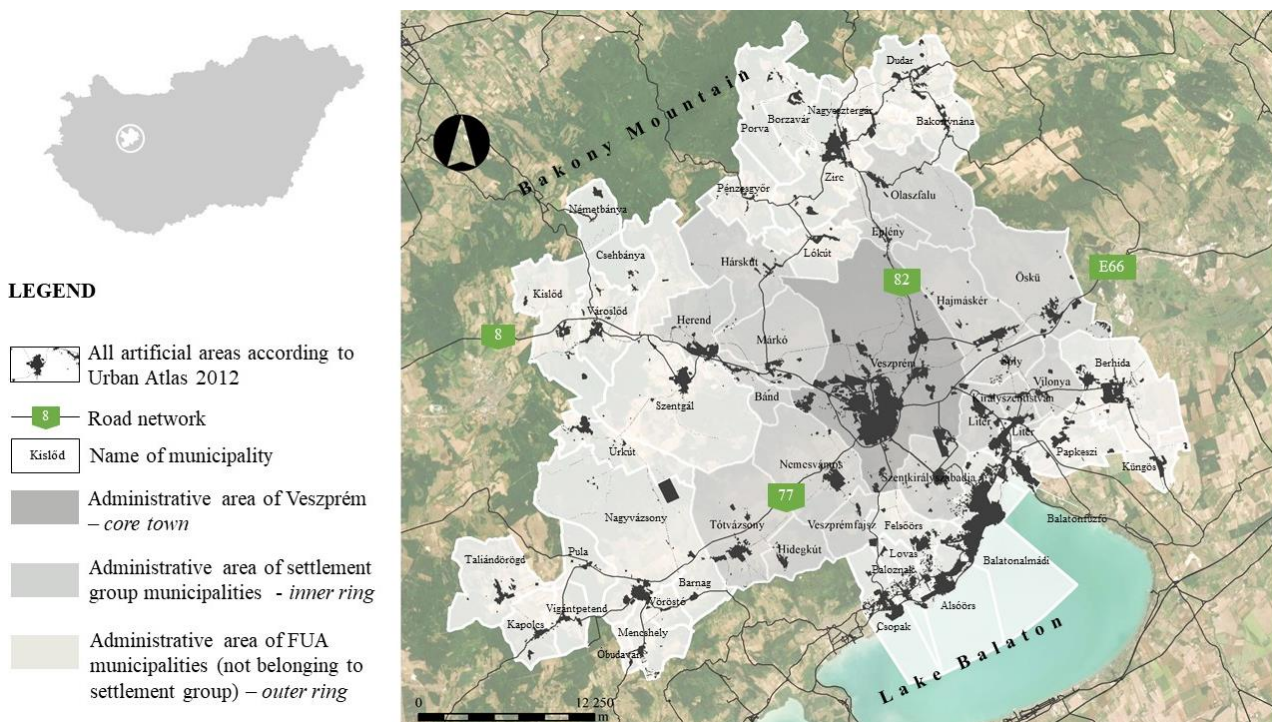


Fig.1 Analysed areas: Veszprém – core town, Settlement group– inner fringe and FUA fringe– outer fringe on Google Earth view

Table 1 The applied land use categories of the analyses, based on Corine nomenclature

Code	Corine nomenclature			Simplification and terms in the research		
	Class 1	Class 2	Class 3 (relevant within Artificial surfaces)	Main categories	Further categories	
1.1.1	Artificial surfaces	Urban fabric	Continuous urban fabric	Artificial surfaces	Urban fabric	
1.1.2			Discontinuous urban fabric			
1.2.1		Industrial, commercial and Transport units	Industrial and commercial units		Artificial surfaces	Transport units
1.2.2			Road and rail network and associated lands			
1.2.3			Port areas			
1.2.4			Airports			
1.3.1			Mine, dump and construction sites			
1.3.2		Dump sites				
1.3.3		Construction sites				
1.4.1		Artificial, non-agricultural vegetated area	Green urban areas		Artificial, non-agricultural vegetated area (abbr. urban green areas)	
1.4.2			Sport and leisure facilities			
2.1		Agricultural areas	Arable land		Agricultural areas	
2.2			Permanent corps			
2.3			Pastures			
2.4	Heterogenous agricultural areas					
3.1	Forest and semi natural areas	Forests	Natural, semi natural areas (abbr. natural areas)			
3.2		Scrubs and/or herbaceous vegetation associations				
3.3		Open spaces with little or no vegetation				
4.1	Wetlands	Inland wetlands				
4.2		Maritime wetlands				
5.1	Water bodies	Inland waters				
5.2		Maritime waters				

available only for the year of 2012. That is why the Urban Atlas was used for visualisation of artificial surfaces (Code begins with 1). The extent (in ha) was calculated with the help of ArcMap software. Excel software was used for further calculation of the ratio of the changed areas. To evaluate the relation of the land use changes and regulatory maps manual comparison was used, because the regulatory maps were in raster dataset available. Furthermore, after manual check of each change of artificial land use in Google Earth and in actual land use maps of municipalities some corrections were needed because of the marked construction sites. For example, the polygon EU-176485 marked a construction site in the year of 2000 transformed to urban fabric for 2018. During the analyses the current or planned (in land use maps) state was taken into account.

According to these categories the spatial distribution of the land use system (area of the municipalities of functional urban area, FUA; settlement group municipalities and central town) was analysed and the most important tendencies between 1990 and 2018 were identified. With the use of this method the urban sprawl around Veszprém was shown.

RESULTS

In present study the land use changes were analysed for the area of FUA, settlement group of Veszprém and administrative area of Veszprém. Changes of FUA (outer) fringe (FUA without settlement group area) and settlement group (inner) fringe (settlement group without the core town, Veszprém) were also described.

The ratio of different land use categories

Most significant changes described between 1990 and 2000, with about 5500 ha in FUA and 785 ha in Veszprém, but more than 90% of all changes stayed within the land use category, defined as unchanged. During this period the tendencies show similarity in the core town and its broader neighbourhood. The increase of natural and artificial areas is almost balanced, the new areas occupied former agricultural areas in the FUA. In parallel in the fringe of the settlement group the artificial surfaces show higher increase. Important fact is, that without the core town there were no change in natural areas within the settlement group (inner fringe), however in the outer fringe there were 167 ha

new natural plots shown, representing 90% of all new natural areas. In Veszprém the artificial areas have remarkable increase with more than 15% of all changes within its administrative border; agricultural areas did not change (Fig. 2, Table 2).

Between 2000 and 2006 the changes are modest; however, the ratio of unchanged areas is the lowest during the examined period – the lowest in the settlement group with about 75%. Remarkable, that during this period no new natural and agricultural area were detected, only the ratio of new natural and agricultural areas grew. Only at broader surrounding of Veszprém were new natural and agricultural areas identified – at FUA fringe more agricultural, at the settlement group fringe more natural ones.

The period of 2006-2012 can be described by intensive increase of artificial areas. Not only in Veszprém (41.7 ha) but at the settlement group fringe (35.9 ha) and FUA fringe (52.2 ha) significant changes are seen. In addition to this only at FUA fringe were new agricultural areas detected. There were no new agricultural and natural areas at inner fringe and core town.

In the last 6 years, between 2012 and 2018, the area of new artificial surfaces has grown further – altogether 136 ha concentrated in the surrounding of Veszprém, and the quantity of new natural surfaces also increased: in Veszprém 97.5 ha, in settlement group fringe 33.3 ha and in FUA fringe 55.3 ha was identified.

According to our analyses focusing on new artificial areas the tendency of changes is different in the examined zones. The most intensive increase of artificial surfaces is identified in the settlement group fringe, in the direct neighbourhood of Veszprém (Table 3, Fig. 3). The trend shows intensive boom of new artificial areas after 2000, between 2000 and 2018 with a growth of 111 ha in FUA fringe, 185 ha in settlement group fringe and 135 ha in Veszprém. The changes show different tendencies, the settlement group fringe shows increase in the last 6 years, however in Veszprém a modest increase and in FUA fringe decrease is experienced. In the last period the structure of the artificial areas also differs from each other: the highest ratio of new areas is urban green in FUA fringe, urban fabric in settlement group fringe and industrial in Veszprém after 2012.

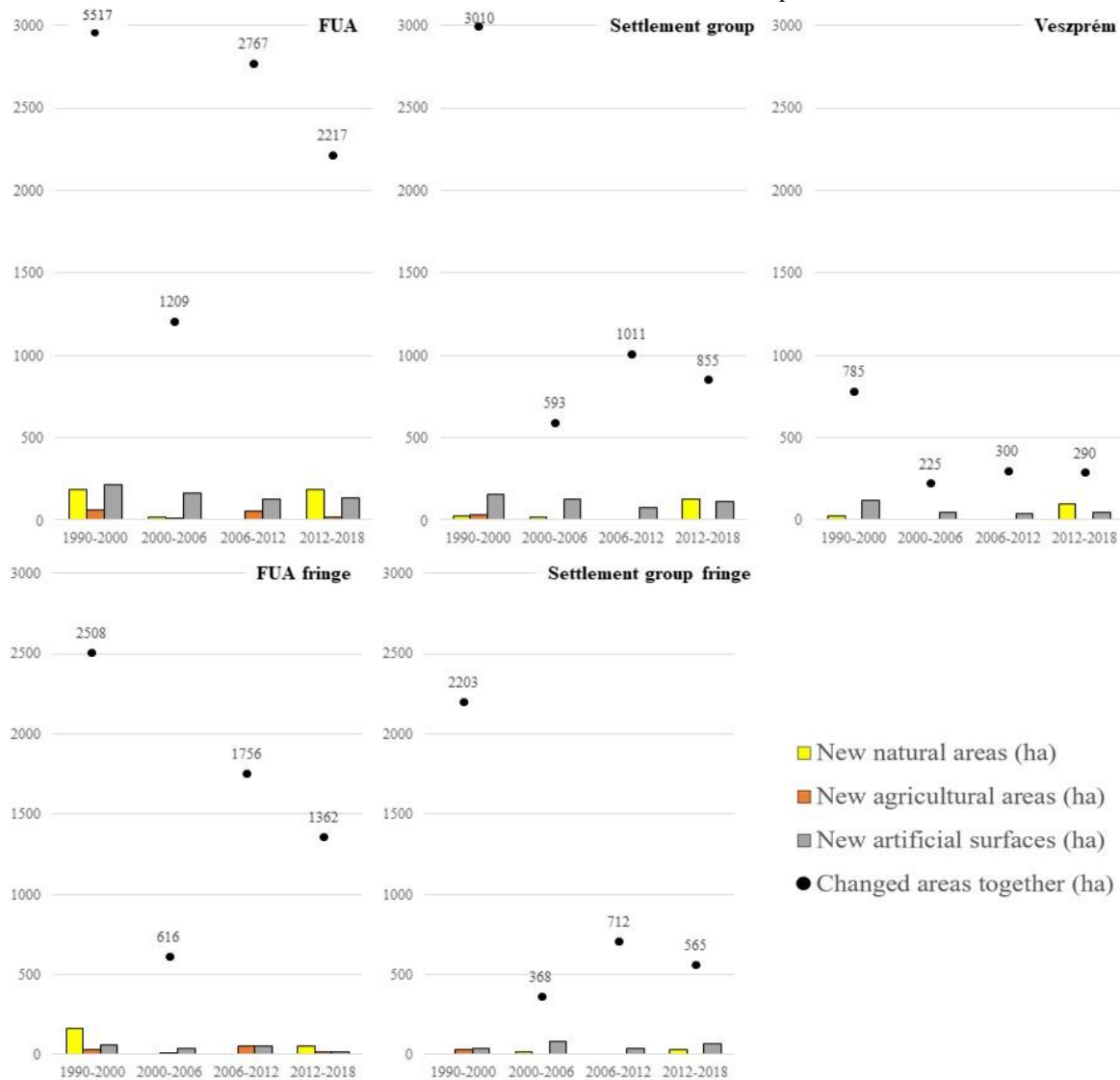


Fig.2 Land use changes focusing on new natural, agricultural and artificial areas at Veszprém and its surrounding between 1990 and 2018 (Data source: Corine, Google Earth)

Table 2 Land use changes in different agglomeration zones according to main categories expressed in ha and ratio of the whole area of the agglomeration zone (Data source: Corine, Google Earth)

	1990-2000	2000-2006	2006-2012	2012-2018
Core town				
New natural areas	21.85 ha / 0.172%	0.0 ha / 0.000%	0.0 ha / 0.000%	97.5 ha / 0.768%
New agricultural areas	0 ha / 0.000%	0.0 ha / 0.000%	0.0 ha / 0.000%	0.0 ha / 0.000%
New artificial surfaces	119.4 ha / 0.941%	46.4 ha / 0.366%	41.7 ha / 0.328%	47.3 ha / 0.373%
Unchanged	665.8 ha / 5.245%	178.3 ha / 1.405%	257.8 ha / 2.031%	144.9 ha / 1.142%
Changed areas together	807.0 ha / 6.358%	224.7 ha / 1.771%	299.5 ha / 2.360%	289.7 ha / 2.283%
Inner ring				
New natural areas	0.0 ha / 0.000%	18.8 ha / 0.045%	0.0 ha / 0.000%	33.3 ha / 0.081%
New agricultural areas	29.6 ha / 0.072%	0.0 ha / 0.000%	0.0 ha / 0.000%	0.0 ha / 0.000%
New artificial surfaces	37.0 ha / 0.090%	79.9 ha / 0.194%	35.9 ha / 0.087%	69.0 ha / 0.167%
Unchanged	2136.1 ha / 5.180%	269.5 ha / 0.653%	675.8 ha / 1.639%	463.0 ha / 1.123%
Changed areas together	2202.7 ha / 5.341%	368.1 ha / 0.893%	711.7 ha / 1.726%	565.3 ha / 1.371%
Outer ring				
New natural areas	167.2 ha / 0.216%	0.0 ha / 0.000%	0.0 ha / 0.000%	55.3 ha / 0.072%
New agricultural areas	33.6 ha / 0.043%	4.2 ha / 0.005%	53.1 ha / 0.069%	20.1 ha / 0.026%
New artificial surfaces	59.9 ha / 0.077%	39.3 ha / 0.051%	52.2 ha / 0.068%	19.7 ha / 0.025%
Unchanged	2247.1 ha / 2.904%	572.6 ha / 0.740%	1651.0 ha / 2.134%	1266.9 ha / 1.637%
Changed areas together	2507.9 ha / 3.241%	616.1 ha / 0.796%	1756.3 ha / 2.270%	1362.1 ha / 1.760%

Table 3 Land use changes in different agglomeration zones according to categories of artificial surfaces expressed in ha and ratio of new artificial surface in Table 2. (Data source: Corine, Google Earth)

	1990-2000	2000-2006	2006-2012	2012-2018
Core town				
New industrial, commercial units	107.8 ha / 90.3%	31.5 ha / 67.9%	6.7 ha / 16.0%	24.0 ha / 50.8%
New urban green areas	0.0 ha / 0.0%	0.0 ha / 0.0%	0.0 ha / 0.0%	1.9 ha / 4.0%
New transport units	0.0 ha / 0.0%	0.0 ha / 0.0%	23.7 ha / 56.9%	0.0 ha / 0.0%
New mine sites	5.9 ha / 4.9%	0.0 ha / 0.0%	11.3 ha / 27.2%	6.0 ha / 12.6%
New urban fabric	5.7 ha / 4.7%	14.9 ha / 32.1%	0.0 ha / 0.0%	15.4 ha / 32.5%
Inner ring				
New industrial, commercial units	8.2 ha / 22.2%	10.4 ha / 13.1%	6.0 ha / 16.8%	0.0 ha / 0.0%
New urban green areas	28.6 ha / 77.2%	1.6 ha / 2.0%	0.0 ha / 0.0%	6.0 ha / 8.6%
New transport units	0.0 ha / 0.0%	0.0 ha / 0.0%	16.2 ha / 45.1%	0.0 ha / 0.0%
New mine sites	0.2 ha / 0.5%	5.1 ha / 6.4%	13.7 ha / 38.1%	32.9 ha / 47.7%
New urban fabric	0.0 ha / 0.0%	62.7 ha / 78.5%	0.0 ha / 0.0%	30.2 ha / 43.7%
Outer ring				
New industrial, commercial units	0.0 ha / 0.0%	6.3 ha / 16.0%	5.3 ha / 10.1%	0.0 ha / 0.0%
New urban green areas	16.0 ha / 26.7%	0.1 ha / 0.4%	46.9 ha / 89.9%	15.5 ha / 78.7%
New transport units	0.0 ha / 0.0%	0.0 ha / 0.0%	0.0 ha / 0.0%	0.0 ha / 0.0%
New mine sites	12.9 ha / 21.5%	14.7 ha / 37.5%	0.0 ha / 0.0%	4.2 ha / 21.3%
New urban fabric	31.0 ha / 51.8%	18.1 ha / 46.1%	0.0 ha / 0.0%	0.0 ha / 0.0%

It is also worth noting, that the new industrial areas are dominant (more than 50% of new artificial areas) in Veszprém, except the period of 2006-2012, when transport units represent the 57% (24 ha) of all new artificial areas. The ratio and the extent of new industrial areas are marginal at the settlement group fringe and FUA fringe, this fact highlights the strong economic concentration in the examined area.

The expansion of urban fabric is typical at FUA fringe between 1990-2006, but after there is no new plot for this purpose until now. At settlement group fringe urban fabric expansion is experienced between 2000-2006 and 2012-2018, just the same as in

Veszprém. During the period of the economic crisis, between 2006-2012 there were no new urban fabric plots at all.

It is also interesting, that urban green (new areas for urban green, sport and leisure facilities) is relevant at FUA fringe areas. During the years of the economic crisis 90% of new plots (47 ha) fall within this category. These plots— for example golf clubs, tracks — are usually located further from the in-built area of the municipalities. However, the same tendency is visible at the settlement group fringe between 1990 and 2000 (77%, 28.6 ha). In Veszprém the new urban green is negligible in all examined periods.

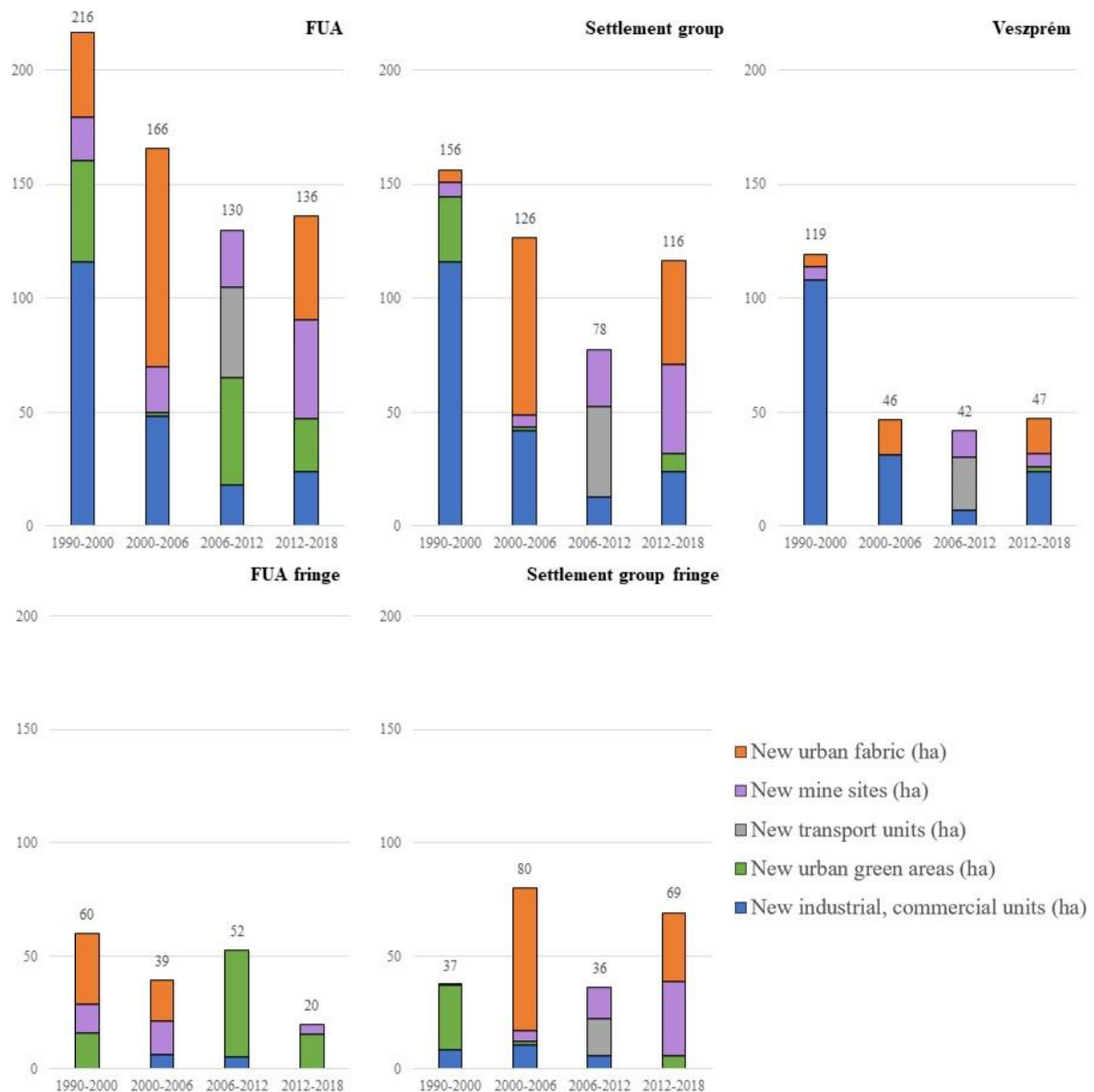


Fig. 3 Land use changes focusing on new artificial areas: industrial, commercial units, urban green areas, transport units, mine sites and urban fabric at Veszprém and its surrounding between 1990 and 2018 (Data source: Corine, Google Earth)

The spatial pattern of the changes

As the map shows (Fig. 4, 5) new artificial areas are situated around the in-built areas of municipalities. Exceptions are found, especially from the period of 2006-2012 and 2012-2018. It is also remarkable, that the density of the new artificial areas is higher on the edge of the in-built areas of Veszprém, at the coast line of Balaton and the main roads of Nr. 8 (to Kőrmend), E66 (to Székesfehérvár and Budapest) and 77 (to Nagyvázsöny). At the Northern part of the study area, Némethánya, Zirc and Dudar have new artificial areas from 1990, among which Zirc seems to have continuous development.

Analysing the distribution of these areas (Fig. 5), it can be stated, that new industrial and urban fabric areas are strongly connected to existing built in areas of municipalities, and former existing industrial sites from the socialism. At outer ring new industrial and commercial areas appeared only in municipalities, that

has industrial tradition (Balatonfüzfő, Nagyvázsöny). In addition to this, new mining and transport sites are so called 'green field' development – set on agricultural or natural areas. Important fact, that urban green areas are also situated far from the core in built areas, and dense urban fabric, also transformed from non-artificial surfaces.

Policy responses for sustainable land use management

There are several tools to control urban sprawl in Hungary. The most important on country level is the renewed Act on Land Use Framework Plan of Hungary and Priority Areas (Act Nr. CXXXIX. 2018), that tries to guide the settlements developing according to the compact settlement structure. This act aggregates the interest of different fields, like nature conservation, agriculture, forestry etc. In our comparison analysis, the Act, adopted in 2003 was used, to be able to follow the effectiveness of regulation (Act XXVI on Land Use Framework Plan of Hungary from 2003).

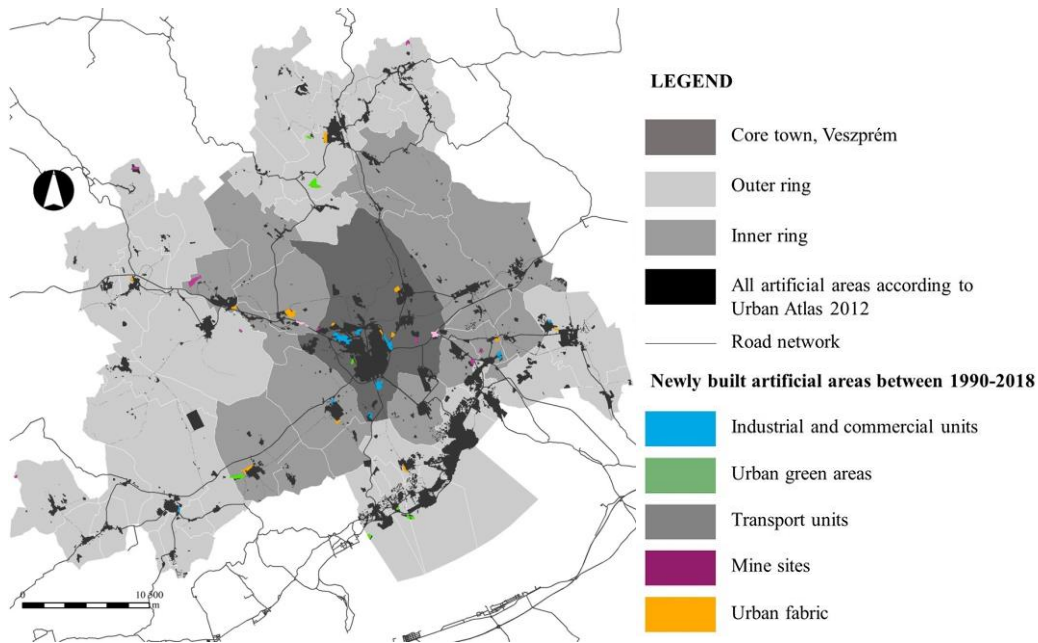


Fig.4 Categories of newly built artificial areas between 1990-2018 in core town, inner ring and outer ring, illustrated with all artificial surface based on Urban Atlas 2012 (Data source: CLC changes layers 1990-2018, Urban Atlas 2012)

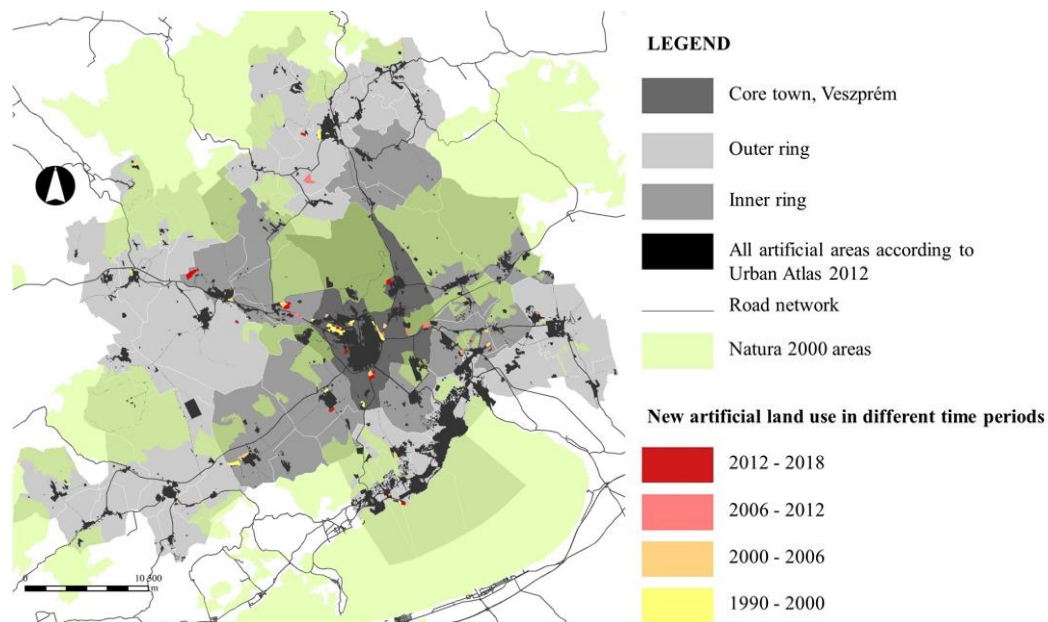


Fig. 5 Newly built artificial surfaces in different time periods, in core town, inner ring and outer ring and Natura 2000 areas, illustrated with all artificial surface based on Urban Atlas 2012 (Data source: CLC changes layers 1990-2018, Urban Atlas 2012, természetvedelem.hu)

The municipalities have to follow the regulations of the national spatial plan. Although the frame is given, the municipalities have a considerable freedom in management of the land use system in their administrative area by elaborating urban management plans (urban development plan, land use plan and building plan). The land use changes were also compared with the land use plan of Veszprém from 2005.

The Natura 2000 network initiated by the European Union’s Habitats Directive, 92/43/EEC, and Birds Directive 2009/147/EC was defined on national level. In Hungary some activities require authorisation from competent nature protection authority and require habitat

management plans. Certain activities (like hunting, fishing, tourism or mining) are possible if it is compatible with the protection. At our examined area (Fig. 5) only some new mining and transport plot falls on the area under Natura 2000 protection.

The National Ecological Network Zone (Fig.6) – that contains inter alia all the Natura 2000 areas – permits land use that are compatible with the preservation of natural values, however different regulations are applied for the core areas, buffer zones and ecologic corridors. After 2000 several land use changes fall on these areas, urban fabric, transport areas, mining units, even industrial and commercial sites.

The Land Use Framework Plan of Hungary, 2003 appointed zones for forests and arable land of exceptional quality (Fig.7). The High-Quality Forests Zone prohibits construction, the High-Quality Arable Zone allows exceptional building with permission of authority. After 2000 no new artificial areas appeared within these zones. However, at the examined area not a great extent of high quality arable can be found.

A new tool of Land Use Framework Plan of Hungary, 2003 was the opportunity for common planning (Fig. 8) for agglomerations and settlement groups defined by the Hungarian Statistical Office. In Hungary there are not really good examples and practice for a such strong common planning activity among municipalities. Maybe that is the cause, that no one had chosen this opportunity, nor Veszprém. The National Land Use Plan (Fig. 9) marked the new main road (E66) without exact path and supplementary infrastructure.

Veszprém’s land use plan was adopted in 2005 in accordance with the National Land Use Plan. That is why the presented study focused on the period between 2006 and 2018. During these years altogether 87 ha area was turned to artificial according to the authors’ evaluation. Most of these changes (81%) followed the spatial structure of the land use plan. Specific sites turned to mining and transport areas between 2006-2012 from semi natural areas do not fit into the foreseen spatial structure of the masterplan. It is also considerable, that these plots were formerly Natura 2000 areas. Another example is the new area of Veszprém Zoo, that was turned to urban green area from forest for recreational purposes. Despite of the negative examples the new artificial areas are directly connected to the morphological urban area and urban sprawl is controlled, as it was foreseeable in the land use plan from 2005 (Fig. 9).

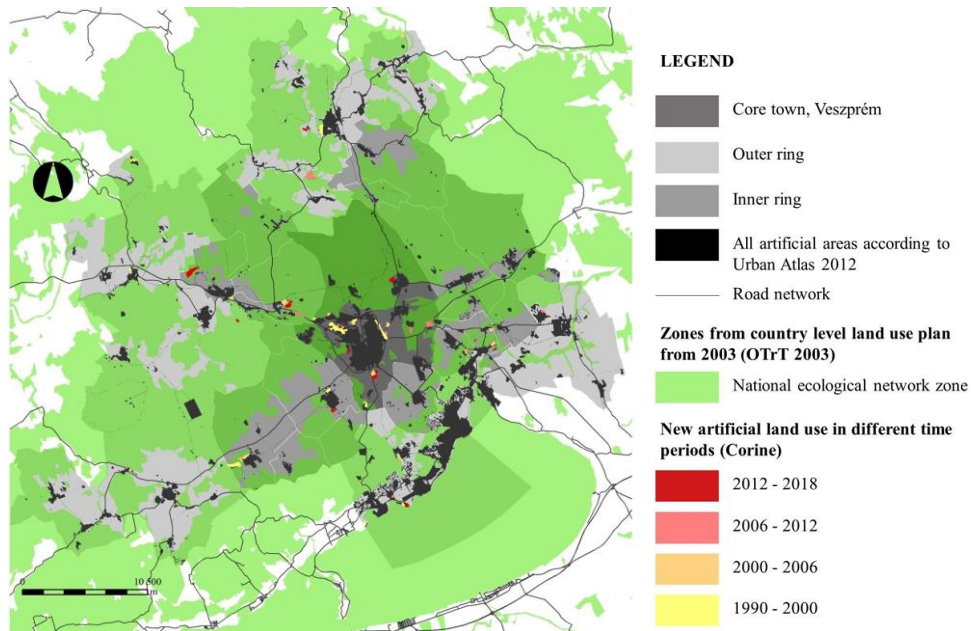


Fig.6 National Ecological Network Zone from National Land Use Plan 2003 and new artificial surfaces in the study area

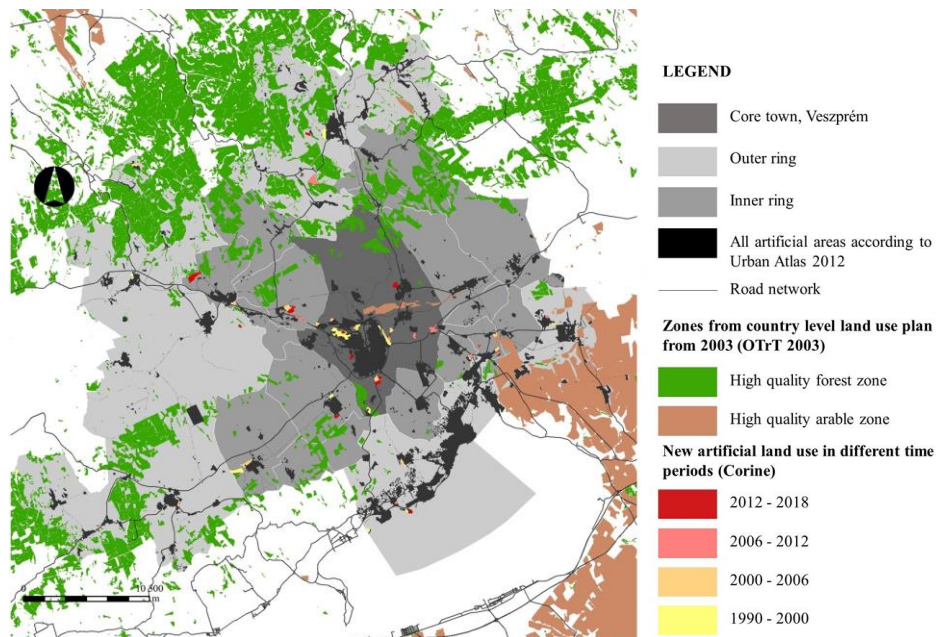


Fig.7 High Quality Forests and Arable Land from National Land Use Plan 2003 and new artificial surfaces in the study area

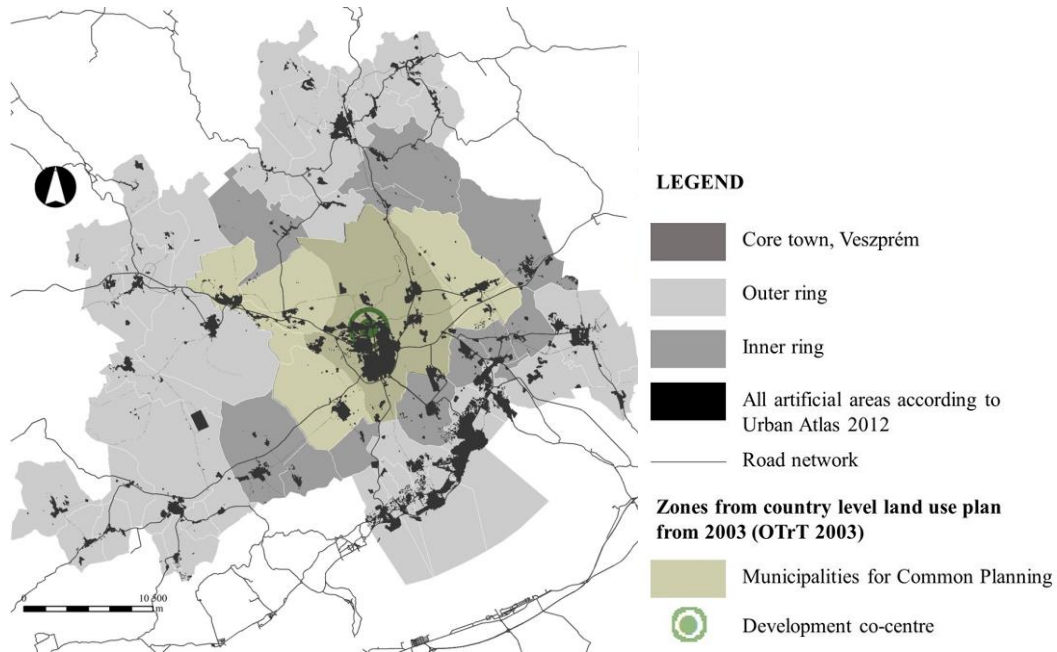


Fig.8 Zone for Region for Common Planning from National Land Use Plan 2003 in the study area

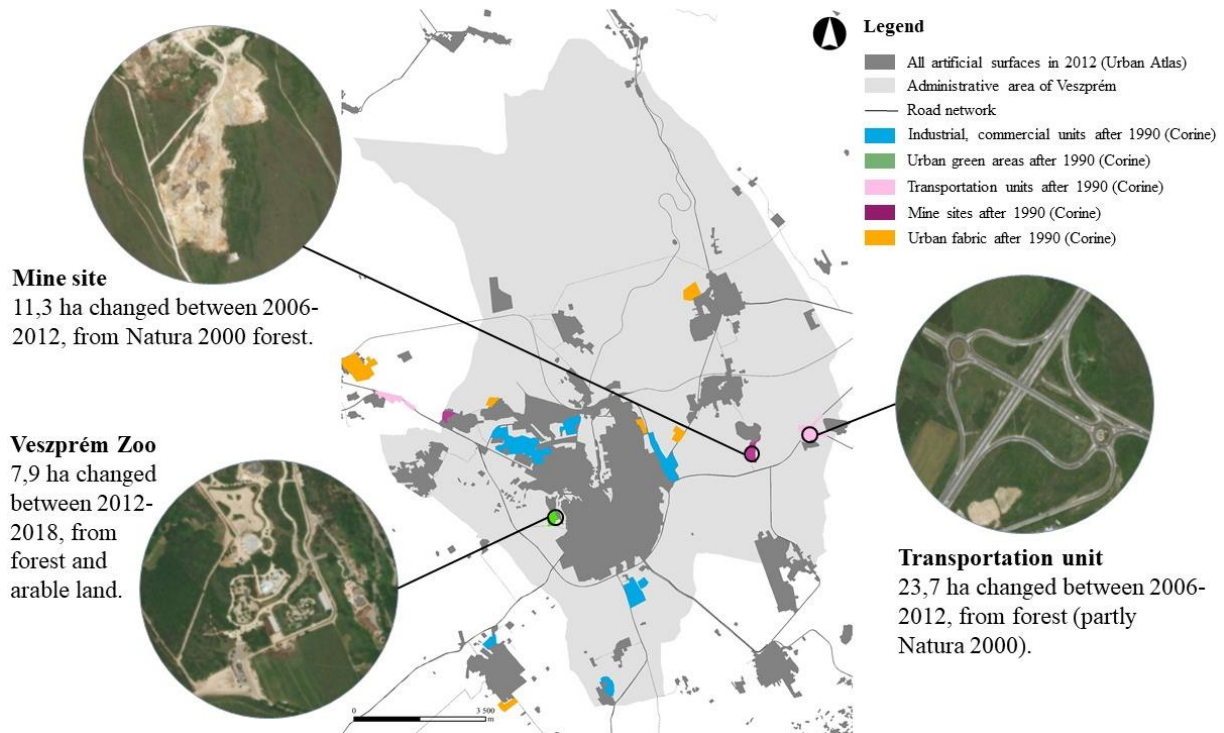


Fig. 9 Artificial land use changes are not fit into the Veszprém land use plan from 2005

DISCUSSION AND CONCLUSION

In the presented research the urban sprawl around Veszprém is detected with the help of land use changes from Corine database, visualised with Urban Atlas map from 2012. The artificial surface is larger in Veszprém, than at inner fringe, the lowest in outer fringe, mostly with the loss of agricultural and natural surfaces.

The most intensive period is the restructuring after socialism, between 1990 and 2000. Important changes are detected during the economic crises, between 2006 and 2012, when the land use moved to the direction of artificial surfaces, especially at the core town and inner

fringe. We can state that the crises consumed the agricultural areas – 95 ha agricultural and 35 ha natural area was turned to artificial. In the last six years the growth of artificial surfaces continued, however new natural areas appeared in Veszprém and in the outer fringe. Agricultural areas are the losers of land use changes, and this finding fits to the European and Hungarian trends (ESPON 1.1.2. 2006; Ricz et al., 2009).

The period of 1990-2000 is the age of reorganisation and industrial renewal, that meant a surface intensive growth in and around Veszprém. In European level the changes are not outstanding (ESPON EU-LUPA, 2014; Grigorescu and Kucsicsa, 2017) and in Budapest similar

trend is detected (Szilassi, 2017). Because of the rural characteristic of the outer fringe, the new natural areas are dominant (more than 78% of new artificial areas after 2006), however artificial and agricultural areas can be also detected. In the inner fringe the characteristic moved to agricultural and artificial surfaces, in Veszprém more to the direction of artificial surfaces. After 2000 the inner fringe gained several new artificial plots, and we found the patterns of a municipality driven housing in the core town. After 2006, the new artificial areas showed different quality. No new housing plots appeared, even in the core town, however new transport and mining units were characteristic, also some urban green and recreational areas at fringe. These changes can be explained by the effects of economic crises, and the dominance of EU Funds, from these were the transport investments financed presumably. In the last six year, in parallel with the continuous and balanced growth of core town, in the inner fringe new artificial surfaces became remarkable again (70 ha), however, the urban development of outer fringe seems to slow down.

If the distribution of new artificial spaces is examined, different tendencies are experienced at outer, inner fringe and core town. The industrial development – according to our data – is concentrated in the core town, that is the pole of the examined region.

The most intensive period of this concentration – due to the inherited socialist sites and central driven development – is between 1990 and 2000 in Veszprém. The inner fringe can be described as the place for living, also has some industrial development, but not dominant. The outer fringe started to be favourable for living purposes, however lagging behind the core and inner areas, only few plots were transformed to industrial. At the time of industrial reorganisation of the capitalism and during the last 6 years no new industrial sites appeared. The recreational function strengthened in these areas thanks to several new artificial green areas for recreation.

An interesting tendency is the change of new sites for urban green, sport and leisure facilities. These are not situated in the in-built areas – the scale of Corine database even not suitable to detect such minor changes – but are found on natural areas, further from morphological urban area. In Veszprém only between 2012 and 2018 is dedicated a plot to this purpose, for the above-mentioned Zoo. In the inner fringe significant period is between 1990 and 2000, after 2000 only minor plots were turned to urban green. At FUA fringe the tendency is almost opposite; between 2006 and 2012 a boom is seen. This artificial land use category is dominant also after 2012, but the extent of changed areas dropped. Some of these areas were turned to golf club, camping sites, or track for horse racing.

Transport development dominated during the crises, mostly financed by EU. In addition, these developments also concentrate more to the core town, than inner fringe. The new plots for mining are scattered during the periods and in the fringe of agglomeration. It is not surprising, that most of the new sites for mining appeared between 2012 and 2018, because for this region the typical natural resource is raw material used in constructions.

The development of urban fringe also mirrors the tendencies of economic changes. During the period of crisis, no new plots were opened for urban fabric. During the period of 1990 and 2000 the outer ring seems to be preferred, 31 ha new urban fabric appeared. This has almost halved for the next period, and no new urban fabric was detected during the crises. In the last 6 years it did not become popular, but some new areas were dedicated for living. At inner ring the suburbanisation and thanks to this new plot came up during 2000–2006 and 2012–2018. In Veszprém – not to count the years of crises, the quantity of new areas for urban fabric was continuously growing. The intensive growth between 2000 and 2006 of urban fabric was the result of municipality policy. The well-known national policies for family support after 2012 – for example CSOK support (financial aid for buying flat/house for families) – do not have any effect on the outer fringe, but in inner fringe and core town is visible through land use changes.

Not surprising the spatial pattern of developments. The new industrial and residential areas are strongly connected to the morphological urban area and main roads. Furthermore, the location of new industrial sites follows the socialist heritage and are mostly opened in the neighbourhood of former industrial units. This can be explained with the importance of transport and logistic facilities nearby, as an economic incentive at other Hungarian towns, Miskolc and Győr as well (Lux, 2014).

The transport units, mining sites and urban green areas are scattered in the rural areas. According to the result, the most vulnerable areas of urban sprawl are at catchment area of main roads outside the town in urban fringe.

Effectiveness of tools of land use control were also analysed, however several soft solutions also exist outside the well-known land use plans and nature protection areas. In the future it would be worth to make a deep analysis of the different land use plans and their modifications. In present study emphasis was put on the most important zones from 2003 and the core town from 2005. According to this the High-Quality Forests Zone had the strictest regulations that was successful, because no new artificial surface appeared. The High-Quality Arable Zone was not so strict, and not dominant at the examined area, however, was successful because these valuable areas did not turn to artificial. Almost the same regulation was at the case of Ecological Network Zone – except the buffer zone where building-in is allowed. This might be the reason for several plots turned to artificial on these areas. Typically mining sites and transport units appeared at the Natura 2000 protection areas. The Zone for Region for Common Planning did not reach its aim at all. At the case of Veszprém the land use plan was able to hold new development close to the morphological urban area, however two unplanned construction sites were opened: the E66 road construction and a new mining site near to the main road. However, special regulation for peri-urban areas do not exist, the framework of land use control can be effective, not to mention some special cases. In this term the regulatory possibility in Hungary are better than in Estonia, where planning control is

missing (Roose et al. 2013) or in Poland where only 30% of municipalities have land use plans (Filepné et al. 2018).

Beside the land use plans and regulations economic changes have also great effect on land use changes. For the future it would also be necessary to prove our assumptions with statistical data, exploring correlation between the land use changes and economic development or social trends. The research was focused on the FUA of Veszprém, but a comparison analyses could have new results. Based on Veszprém's unique development and geographical situation assumptions could not be made to the whole country – the neighbourhood of Balaton agglomeration with one of the strongest regulation for nature protection and land use or the relatively large military area at the Northern part also affect the land use trends.

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INTEGRATED APPROACH TO ESTIMATE LAND USE INTENSITY FOR HUNGARY

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Abstract

An integrated approach was applied in this article to provide a medium-scale map of land use intensity for Hungary. The main goal was to estimate its value by a small set of parameters, which are freely available and have a high resolution. The basis of the evaluation was the CORINE 2012 dataset, and a matrix method was applied to integrate the ratio of natural/semi-natural vegetation, woody vegetation and the Natural Capacity Index in the assessment to describe the complex approach of land use intensity. The medium level land use intensity map provides information for decision makers/landscape planners on the current status and spatial pattern of anthropogenic impact and indicates those hot-spots where land use intensity is high and should be focused research and management to intervene in order to encourage sustainable land use. 46% of the arable lands in Hungary show the most intensive land use. Comparing the map with the previously published hemeroby map of Hungary, more intensive impact on landscape transformation through human action was found. In agricultural areas both researches agree that the intensity and human activity is really high, and the lowest intensity class is rare in Hungary except for mountain regions and protected areas.

Keywords: intensity, matrix method, CORINE, naturalness

INTRODUCTION

Measuring the intensity of changes in land use is one of the key issues considering the assessment of anthropogenic impacts. Without investigation, it is understandable that human influences play a key role in intensifying land use (e.g. global growth of settlements and industrial areas). The intensity of land use can be approached from different content and structural aspects (Erb et al., 2013). Well-known approach is the economic approach, however other attempts to assess the factors driving the intensification of changes (e.g. population, technology), or the anthropogenic and social changes leading to it, are also frequent. Lots of one-dimensional indicators are used to determine the extent of intensity e.g. annual crop yield, rotation length, size of forest and uncultivated areas, frequency of sowing, the magnitude of biodiversity, the size of labour and capital per field, annual production of the area, the climate, soil and technique affecting the crop yield (Herzog et al., 2006; Erb et al., 2012; Verbung, 2013). A key issue concerning intensity is how to measure the impacts of anthropogenic effects on a given region. The methods of solution usually depend on the question to be answered, but the systemic character and the complexity of the affected environment cannot be ignored.

Calculations that include multiple factors into one index are also used to express land use intensity. One such complex index with regard to agricultural

utilization is, for example, the ILI index (Indicators of Landuse Intensity - Herzog et al., 2006) which includes the N content and the pesticide use of a unit area; the "r" index signifying the actual yield and the reference yield under the conditions of strictly determined economic and technological factors (Dietrich et al., 2012). Various landscape indices and irrigation, ploughing and land use change data were also attempted to be combined into another agricultural intensification index with geostatistical methods (Culman et al., 2010). According to the logic used, all of these attempts show to what extent anthropogenic activity changes agricultural productivity. Similar intensity calculations are also known for non-arable areas, the LUI (land use intensity) index is one of them, and it is used for meadows with the data of fertilization, mowing and animal husbandry (Blüthgen et al., 2012). Whatever method is used to measure the extent of intensity, it heavily depends on the topographic scale, the time scale used, and the studied agricultural activity (Temme and Verbung, 2011; Verbung, 2013).

Intensity is a concept that encompasses the use, management, and infrastructure of an area, and a lot of different parameters are known to express it. This study attempts a medium-scale estimation of land use intensity for Hungary. A matrix concept was applied to estimate the land use intensity based on the ratio of natural areas and woody vegetation, further more naturalness for selected land use types in Hungary.

STUDY AREA

Hungary, having an area of 93 thousand km², has a basin character where 80 % of the surface elevation is less than 200 m above sea level. About 75 % – more than 6 million ha – is agricultural area: the arable land, the forest area and grassland are 47%, 21% and 8.5 %, respectively. On 70% of the arable lands intensive, and about 30 % extensive agriculture is typical (Ángyán et al., 2003). The Hungarian basin area is characterized by a medium-scale, intensive arable area divided into parcels with sizes ranging from 1 to 10 ha (van der Zanden et al., 2016). NUTS2 level assessment is not appropriate to allocate the territorial differences in land use intensity. Our evaluation was based on the 2012 CORINE Land Cover 2012 (CLC 2012) database (available for Europe), where out of the 44 land cover classes in Hungary 15 were chosen (Fig. 1), including agricultural areas (211 Non-irrigated arable land, 213 Rice fields, 221 Vineyards, 222 Fruit trees and berry plantations, 231 Pastures, 242 Complex cultivation patterns, 243 Land principally occupied by agriculture, with significant areas of natural vegetation), forest and semi-natural areas (311 Broad-leaved forest, 312 Coniferous forest, 313 Mixed forest, 321 Natural grasslands, 324 Transitional woodland-shrub, 333 Sparsely vegetated areas) and wetlands (411 Inland marshes, 412 Peat bogs). This resolution of data contributed to a medium-scale evaluation of intensity in land use in Hungary.

DATA AND METHODS

Partial input or output data (or a combination of them) for the present analysis were not applied in this study, but we intended to use an integrated approach. The reason behind it is that the majority of the cited research connected some kind of complexity to the concept of intensity (e.g. Newbold et al., 2015). When designing the applied method, it was also necessary to be taken into account that the land use and land cover data available as remote sensing data, mostly used because of efficiency, and cannot be used directly or only to a limited extent to measure intensity changes. Among other things, it is due to the fact that it is difficult to detect the intensity of certain surface types, which manifest in the chemical or management characteristics of soils (Eckert et al., 2017).

The applied data, their source and resolution is presented in Table 1 (CORINE CLC data without artificial areas, the boundaries of areas under nature conservation, and the extent of the woody vegetation based on the dominant leaf type, furthermore the Natural Capacity Index).

The national protected areas, as well as the Natura 2000 SCI areas were applied in the article to allocate the natural and semi-natural areas in Hungary. The boundaries of the woody vegetation were allocated by the Copernicus High Resolution Layers (HrL) data on dominant leaf type. The applied Natural Capacity Index (NCI) essentially expresses the naturalness and size of the spots obtained as a result of the calculation in a size of 36 ha, in a gridded layout (Czúcz et al., 2012). In Hungary the maximum value is 63 (from 100), which means that the degree of

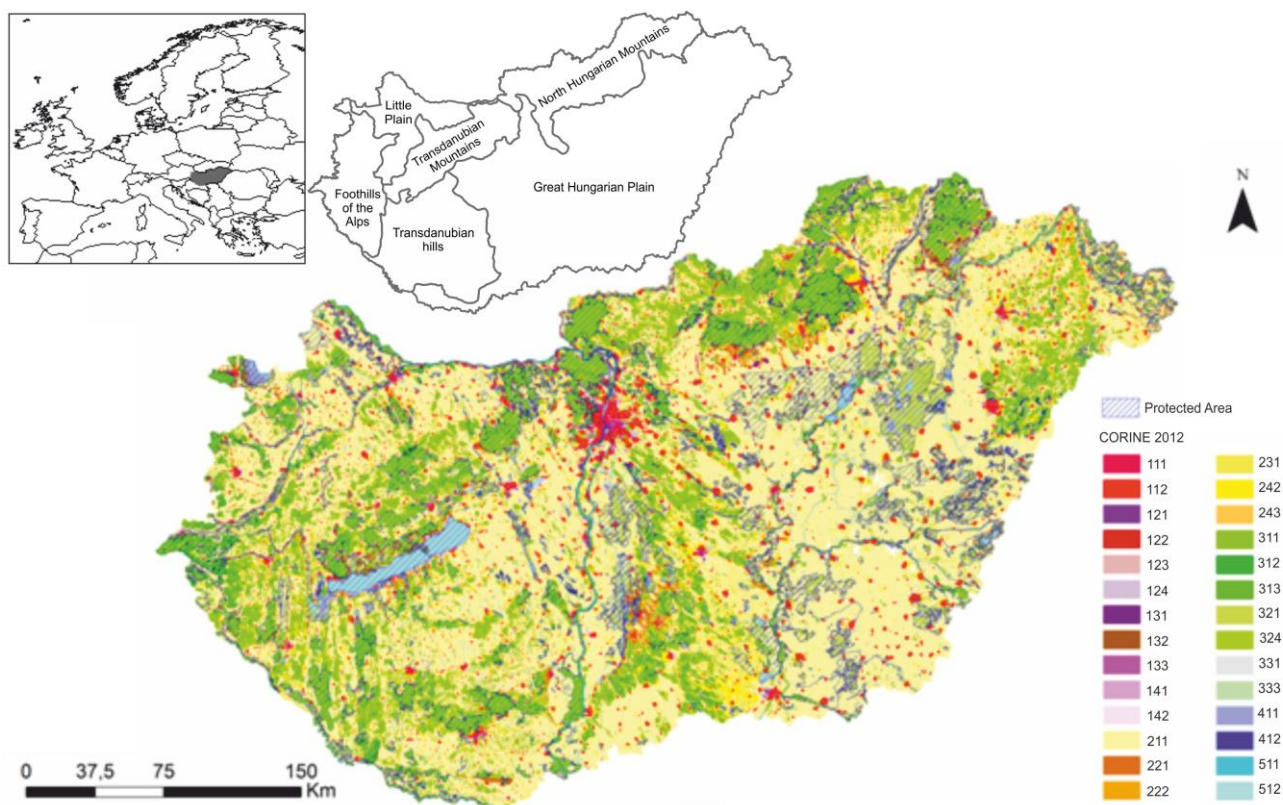


Fig. 1 Study area with the CORINE Land cover classes (CLC 2012) and the combined map of protected areas (Natura 2000 SCI and national park core areas and buffer zones)

Table 1 The applied datasets in the integrated approach

data layers	content	source	date	resolution
CORINE land cover	agricultural areas, forests, wetlands	CORINE CLC 2012 dataset: https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012	2012	25 ha
Natura 2000 SCI	Boundaries of protected natural, semi-natural vegetation	EEA datasets: https://www.eea.europa.eu/data-and-maps/data/natura-9	2017	5 ha
National protected areas	core and buffer zones of national parks	Nature Conservation Information System - http://webgis.okir.hu/tir/	1990s	5 ha
Dominant leaf type	woody vegetation	EEA Copernicus Land Monitoring Service – High Resolution Layer Forest:Product Specifications Document 2018, Sentinel EVI data	2015	20 m
Natural Capacity Index (NCI)	naturalness	Czúcz et al. 2008, 2012	2012	36 ha

naturalness is up to 63% on certain spots. The natural surface of Hungary is less than 3.3% (Böloni et al., 2008).

When developing the method, we wanted to achieve an integrated approach with fewer, well-explained and generally available parameters. In order to achieve this goal, we used a simple method to identify intensity changes, a method that can identify those patches which exhibit more significant changes on a more detailed scale too, and, therefore, can be analyzed for their effect (Kuemmerle et al., 2016). The resulting categories can be compared to Lambin et al. (2001) and with van den Zanden et al. (2016) and the principles of intensity calculations, as well as with the parameters applied.

The workflow of the applied assessment is presented in Fig. 2. The first step was to determine of the percentage of natural or semi-natural vegetation cover for each land cover patch (based on the combined map of protected areas maps: Natura 2000 SCI, the core and buffer zone of the national parks without weighting). As a second step the percentage of woody vegetation cover based on the dominant leaf type HrL product was also assigned to each land cover patch. As step 3, a 5x5 matrix was provided using the ratio of natural vegetation and woody vegetation to all selected CLC 2012 patches. Using the matrix method, the relationship between natural vegetation and woody land cover was investigated. The naturalness of vegetation and the percentage of forest cover were also grouped into 5-5 clusters. The clusters were evenly distributed (0-3%, 3-25%, 25-50%, 50-75%, >75%). Thus, the result has become quite uniform, with an intensive anthropogenic use of the area on scale 1-5. As the last step, the refinement of the matrix results was done by the Natural Capacity Index (NCI) compiled with field surveys (Czúcz et al., 2008, 2012), the results of these detailed recordings at a resolution of 36 ha were used on a 3-km-mesh. NCI data was integrated also with the application of an 5x5 matrix. As a result, the produced classes represent the intensity of land use for all CORINE patches from 1 to 5, where 1 indicates the most intensive land use.

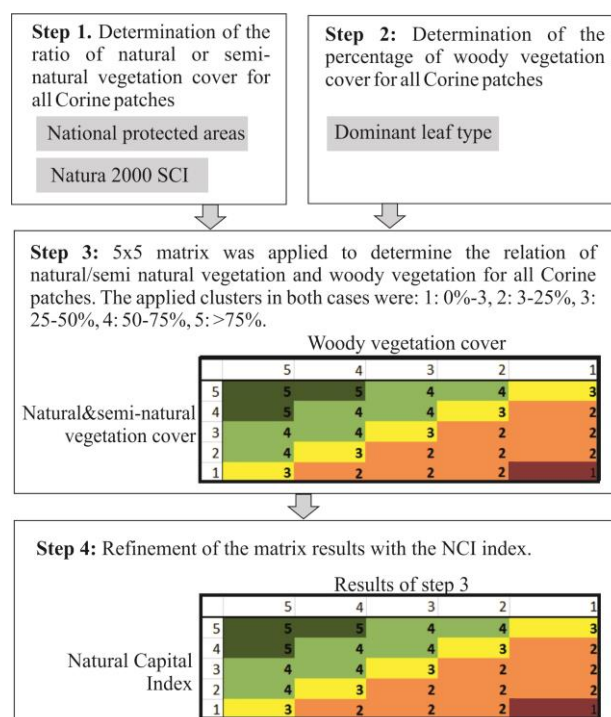


Fig. 2 Workflow of the applied assessment

RESULTS

The ratio of natural and semi-natural vegetation in most agricultural areas (211, 213, 221, 222, 242) is very low (Table 2). Almost 99% of the patches include less than 3% natural and semi-natural vegetation cover. Among agricultural areas, 231 and 243 can be represented with higher ratios of natural or semi-natural vegetation cover, however, still 95% is represented by natural vegetation cover lower than 3%. In this case, however, approx. 2.5% of the CORINE patches are covered with natural vegetation over 75%. For forests, the ratio of natural and semi-natural vegetation is still low in case of the 311, 312, 313 categories, since these are mostly planted forests. But

Table 2 Percentage of CORINE patches according to the 5 natural and semi-natural vegetation cover classes

CORINE 2012	Natural and semi-natural vegetation cover				
	0-3%	3-25%	25-50%	50-75 %	>75 %
211 Non-irrigated arable land	98.60	0.70	0.07	0.14	0.49
213 Rice fields	96.95	0.00	0.00	0.00	3.05
221 Vineyards	99.23	0.10	0.28	0.09	0.30
222 Fruit trees and berry plantations	99.62	0.10	0.06	0.00	0.22
231 Pastures	95.07	0.61	1.02	0.72	2.58
242 Complex cultivation patterns	98.82	0.23	0.16	0.16	0.63
243 Land principally occupied by agr. with sign. areas of nat. veg.	95.68	0.32	0.46	0.98	2.56
311 Broad-leaved forest	79.58	2.35	4.34	7.21	6.52
312 Coniferous forest	81.05	0.36	0.35	0.80	17.44
313 Mixed forest	81.53	0.34	0.61	1.20	16.31
321 Natural grasslands	28.78	0.15	2.58	9.26	59.24
324 Transitional woodland-shrub	89.89	0.48	0.69	0.73	8.20
333 Sparsely vegetated areas	18.59	0.00	1.24	0.00	80.17
411 Inland marshes	50.59	0.38	0.80	1.53	46.70
412 Peat bogs	77.15	7.05	0.12	2.04	13.64

in case of categories 321 and 333 (natural grasslands and sparsely vegetated areas) significant ratio (59, 80%) of the patches are represented with natural and semi-natural vegetation cover over 75%. They are mostly protected areas, only 18-28% of the patches are represented with 0-3% of natural and semi-natural vegetation cover. The extent of 411 and 412 categories are quite small related to all other categories. In more than 50% of their CORINE patches they are represented with natural and semi-natural vegetation cover less than 3%.

The ratio of woody vegetation in most agricultural areas (CLC codes: 211, 213, 221, 231, 242) is very low (Table 3). 85-99% of the patches include less than 3% woody vegetation cover and 0% of the patches have woody vegetation cover over 75%. Only 222 (Fruit trees and berry plantations) show somewhat lower values (78%) for the 0-3% category. In this case, all other classes are evenly distributed, approx. 5%. The

category 243 shows similar values to 222. Among forest areas 311, 312, 313 (mostly planted forests) are characterised by high woody vegetation cover in 74-78%, however, in 13-14% of the CORINE patches show less woody vegetation cover than 3%. In case of 333, almost all patches have no woody vegetation cover, 411 and 412 are characterised by mostly 25-50% woody vegetation cover.

Based on the matrix method the relationship between natural vegetation and woody vegetation cover is demonstrated in Fig. 3. The results represent an intensive anthropogenic use of the study area, more than 70% cover of the category 1, which indicates intensive land use itself. This coincides with the results so far (e.g. Ángyán et al. 2003). After step 3 it becomes obvious that the overall picture on land use intensity based only these two parameters is more complex and shows different pattern than the land cover itself.

Table 3 Percentage of CORINE patches according to the 5 woody vegetation cover classes

	Woody vegetation cover				
	0-3%	3-25%	25-50%	50-75 %	>75 %
211 Non-irrigated arable land	98.13	1.79	0.06	0.02	0.01
213 Rice fields	99.95	0.05	0.00	0.00	0.00
221 Vineyards	94.51	3.87	1.32	0.31	0.00
222 Fruit trees and berry plantations	78.85	4.55	4.88	6.76	4.96
231 Pastures	90.82	5.92	2.41	0.68	0.16
242 Complex cultivation patterns	86.62	7.49	4.71	1.09	0.09
243 Land principally occupied by agr. with sign. areas of nat. veg.	71.16	6.33	14.14	6.89	1.47
311 Broad-leaved forest	13.05	0.53	0.79	7.21	78.43
312 Coniferous forest	13.47	0.29	1.16	9.14	75.94
313 Mixed forest	14.73	0.20	0.70	10.16	74.21
321 Natural grasslands	95.49	3.31	0.98	0.14	0.08
324 Transitional woodland-shrub	41.19	1.97	9.56	20.99	26.30
333 Sparsely vegetated areas	99.86	0.14	0.00	0.00	0.00
411 Inland marshes	89.09	4.88	3.75	1.72	0.55
412 Peat bogs	85.80	9.03	4.19	0.73	0.24

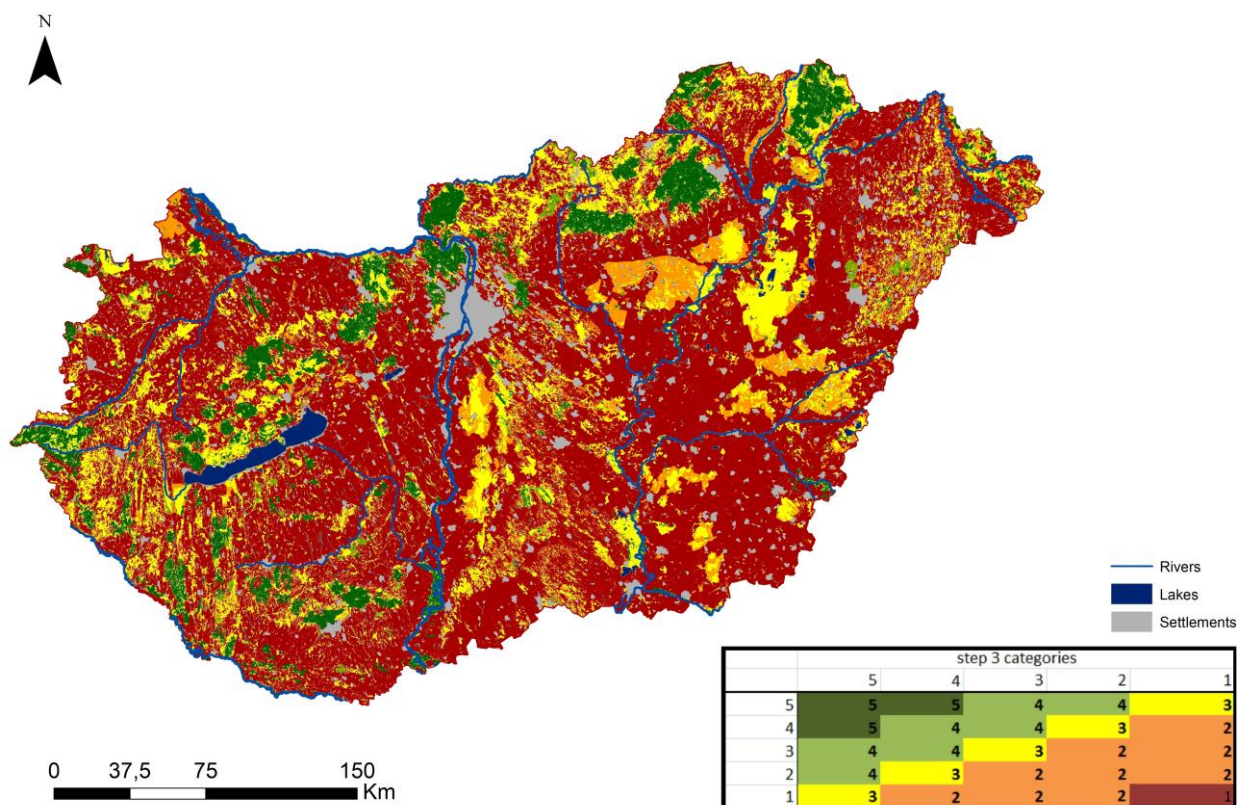


Fig. 3 The result map of step3: application of the matrix method to demonstrate the relationship of natural vegetation cover and woody vegetation cover in all selected CLC 2012 patches

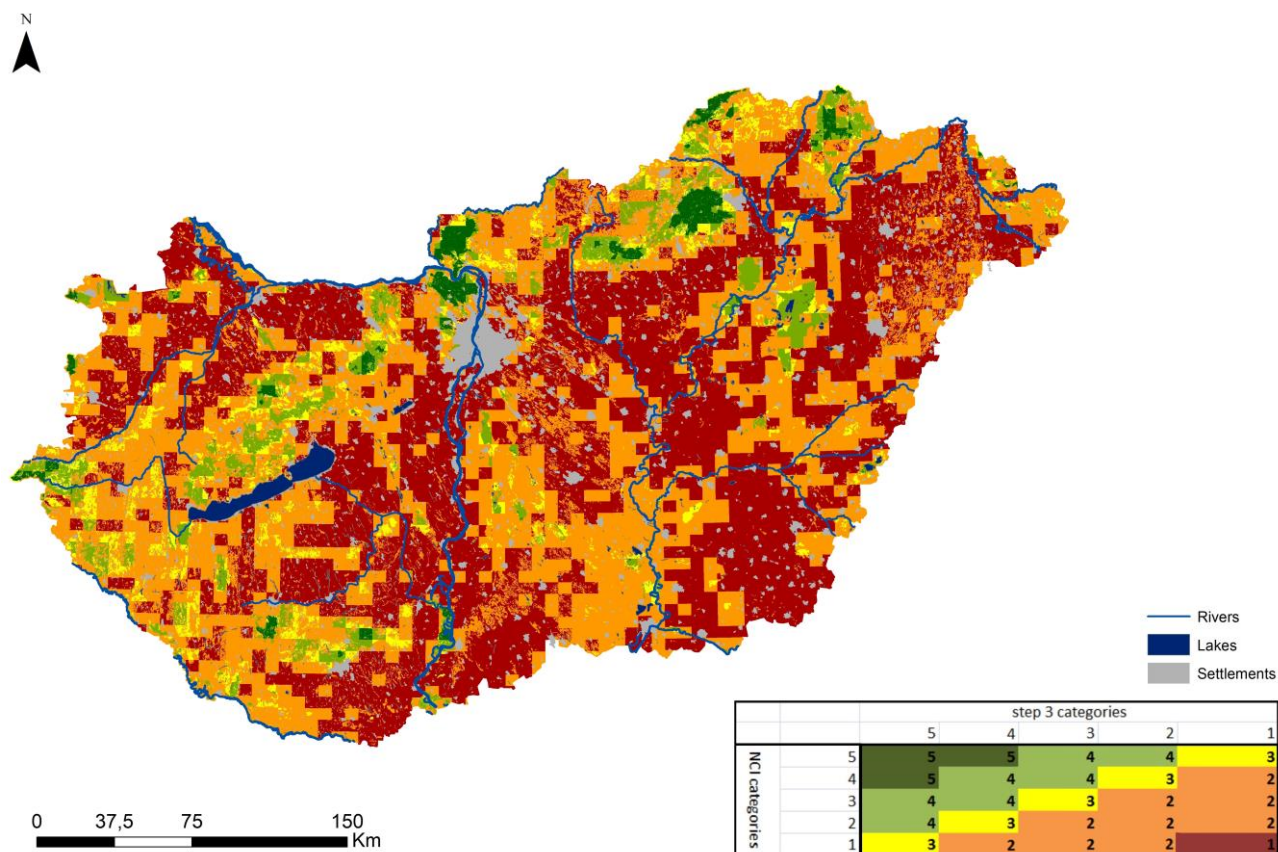


Fig. 4 The result map of step 4: Landuse intensity map of Hungary (1-highest land use intensity; 5-lowest land use intensity)

The final land use intensity map, integrating NCI datasets, is presented in Figure 4. Concerning land use intensity, the mountainous regions of Hungary (Transdanubian Mountains, North Hungarian Mountains, Transdanubian hills) are represented with the lowest land use intensity. The Little Plain located in NW Hungary is mostly characterised by high land use intensity (class 1), in contrary to the Great Hungarian Plain, where we can found larger patches with medium intensity (or even low). The differences in soil attributes are clearly reflected in the resulted datasets: land use intensity on sandy soils, and salt-affected soils is lower compared to the neighbouring areas.

46% of the arable lands (211) in Hungary show the least naturalness, and the lowest ratio of woody vegetation and natural, semi-natural vegetation cover, thus, the most intensive use. It is similar only about 3% of the meadows (231). To show the details of the provided map, a zoom on the area neighbouring Szeged is shown in Figure 5, with an overlay of the CORINE codes 211 and 231, as the most frequent land covers of the Great Plain. This area is a good example of the differences between the different landscapes (here: alluvium, sandland, loess covered areas).

DISCUSSION AND CONCLUSION

For many, it is obvious that areas with strong anthropogenic influences, are characterized by ecological consequences such as the growing destruction of plants, a dramatic reduction in desirable biodiversity, an increase in the isolation of vegetation (e.g. in urban areas). In most cases, biodiversity change is mentioned, as it is

measurable well and its effects can be analyzed. its environmental expectations are clarified even according to EU standards (NATURA. 2000). Several procedures from various areas are known to measure the intensity of land use. In particular, input and output parameters (e.g. crop yield per unit, N content) or their integrated version are used, thus, e.g. the Infrastructural Fragmentation Index (IFI), the Urban Fragmentation Index (UFI), or the Connectivity Index (CI) are defined (De Montis et al., 2017). The fragmentation of the landscape, which includes the fragmentation of larger units into smaller ones and the typical transformation of intensively used areas, is one of the most significant effects on ecosystem services (Jaeger et al., 2016).

We primarily attempted to measure the anthropogenic effects for the characterization of landscape diversity which is in connection with the land use intensity. Therefore, we compared the regional differences of intensity (Fig. 4) with the regional differences of hemeroby (Fig. 6, Csorba et al. 2018), because they both share the same causes in the background.

The hemeroby map by Csorba et al. (2018) shows less intensive impact on landscape transformation through human action, than this research. In agricultural areas both researches agree that the intensity and human activity is really high and the lowest intensity is rare in Hungary (except for mountain regions and protected areas).

More intensive use of cropland, generally determined by high land use intensity, may affect to varying degrees on environmental parameters. For soil

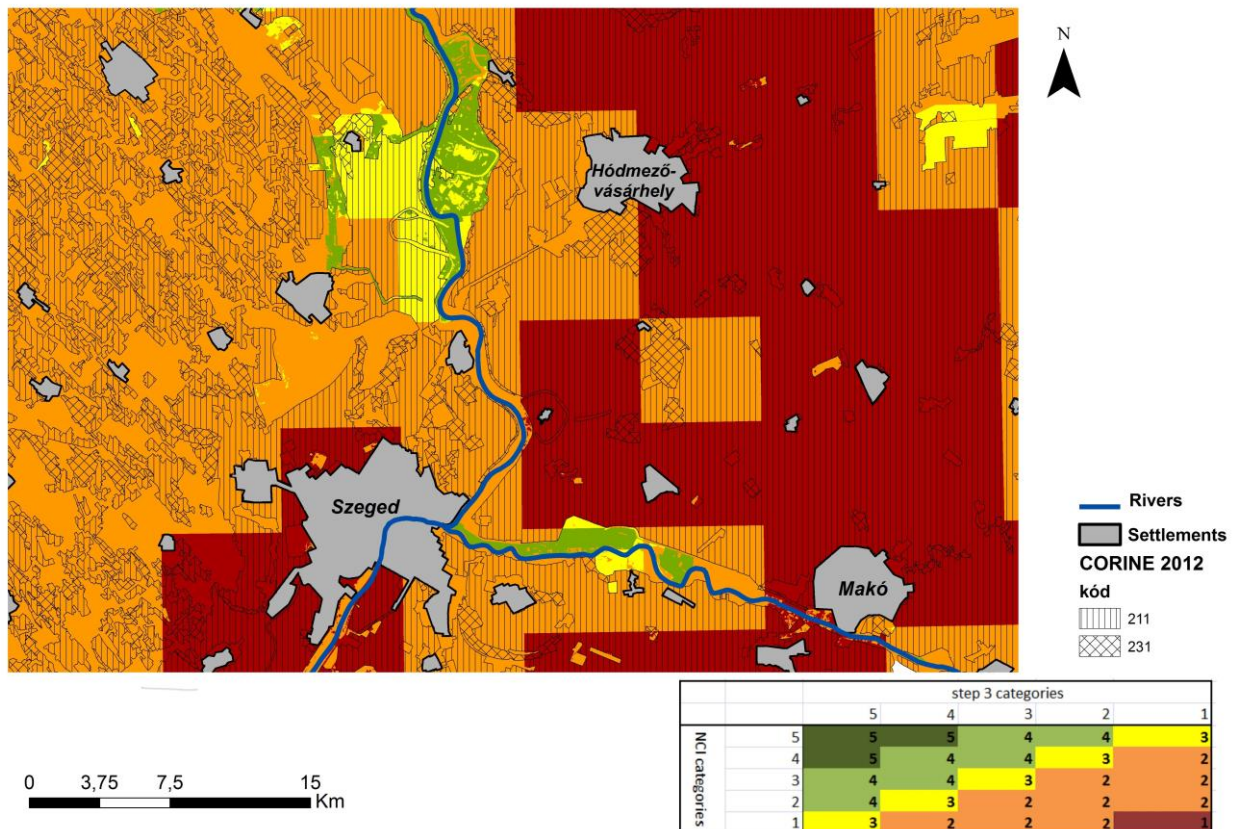


Fig. 5 Land use intensity map around Szeged overlaid with CLC 2012 layers with code 211 and 230

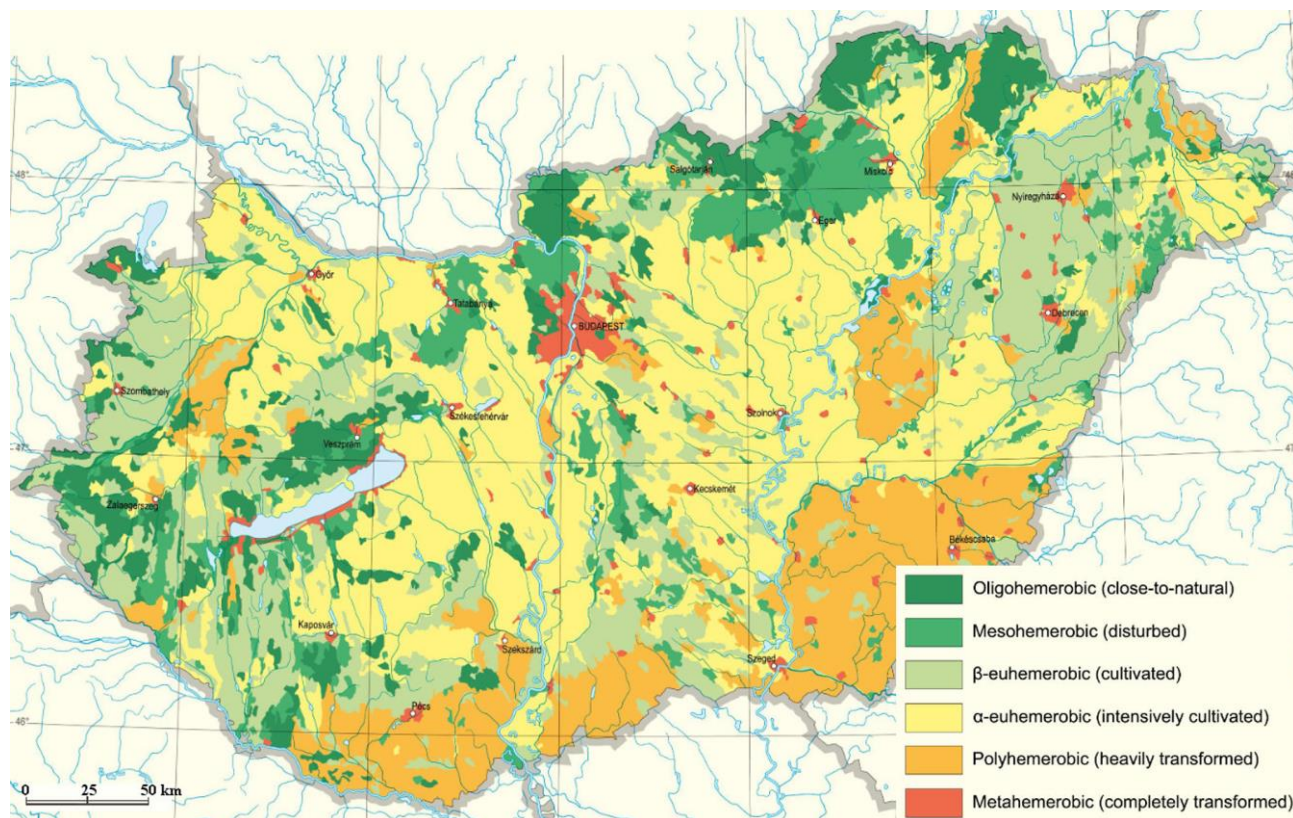


Fig. 6 Intensity of landscape transformation through human action (hemeroby) (Csorba et al. 2018)

e.g. increase in compaction, structure degradation, or the higher level soil of erosion by water. In the case of vegetation, the decrease in biodiversity, growth of uncultivated areas and abandoned areas.

Our results indicates those hot-spots where land use intensity is high in regional scale. These areas should be focused regarding research, management and spatial planning too. With management of low-intensity pasture systems, conservation of high-value habitats and their associated biodiversity, it can be identified where and how to intervene in order to encourage sustainable land use.

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DROUGHTS, DRY SPELLS AND LOW WATER LEVELS IN LATE MEDIEVAL HUNGARY (AND SLAVONIA) III: POTENTIAL DRY SPELLS AND THE DROUGHT OF (1516-)1517

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Abstract

As a continuation of the series about droughts in late medieval Hungary, we present, analyse and compare further cases, based on contemporary direct and indirect documentary source evidence. The data, concerning (potential) low water-level conditions in 1375, 1378, 1393-1394 and 1517, and the economic problems (and solutions) probably related to multiannual dry (spring, summer?) conditions, recorded in the 1410s and 1420s, are further compared to the recent tree-ring based hydroclimate reconstruction of the OWDA (Old World Drought Atlas). Whereas the cases in 1371, 1375, 1378, (1414-)1417 and 1427-1428 (and before) reflect on local-regional problems and also show some conflicts between documentary and tree-ring based reconstructions, in 1393 the local data and the potential Danube low water-level evidence mainly reflects on lower precipitation sums in Western Hungary and the Upper-Danube catchment. The 1517 case, however, presumably refers to large-scale drought problems in the Carpathian Basin and beyond. Beyond the case studies on individual years or multiannual periods, indirect indicators of drought and dry spells are discussed and main groups of most frequent (potential) indicators defined. Preceded by a hard winter, the year of Reformation stands out both in documentary and tree-ring evidence as an outstanding drought year, and has particular importance in the paper.

Keywords: late Middle Ages, dry spells, low water levels, Danube, Sava, documentary evidence, OWDA

INTRODUCTION

In the present paper six cases – reflecting on actual dry conditions, and probably, in an indirect way, referring to dry spells that occurred in the Carpathian Basin – are discussed based on direct and indirect contemporary documentary evidence, and compared to the tree-ring based annually-resolved summer precipitation and spring-summer soil moisture reconstruction of the Old World Drought Atlas (hereafter OWDA; see Cook et al., 2015). The sources of the seventh case reflect on a significant or potentially outstanding drought, around (1516-)1517.

The discussed indirect cases from 1371, 1375, 1378, (1414-)1417, mid-/late 1420s, and the different groups of potential indirect evidence – related to drought years mentioned in the previous two papers (Kiss-Nikolic, 2015; Kiss, 2017) – are mainly based on reports that may indirectly reflect on drought or prolonged dry conditions. A common characteristic of these indirect water-shortage/deficit or dry-spell reports is that all reflect on years when the tree-ring based OWDA evidence, referring to (spring-)summer hydroclimate conditions, show notably dry conditions or even significant drought.

The last case from 1517, with potential, indirect evidence also for 1516, concerns a drought event, where both direct and indirect documentary as well as tree-ring evidence suggest outstanding dry conditions of possibly (or at least) biannual duration. This case is comparable to the greatest drought years of the period between 1450 and 1550, namely to 1473(-1474) and 1540.

SOURCES AND METHODS

In the present paper in all of the cases legal evidence, charters are utilized, mainly related to different economic (or military) activities, strongly dependent on water supply, and partly to more general, larger-scale problems. Consequently, the case studies of the present paper partly refer to drought-related economic problems detected in a relatively small area, in the neighbourhood of a village, while other cases, but especially the one in 1517, discuss severe, possibly countrywide drought problems. Thus, the present study differs from the previous ones not only in the proportionally high relevance of indirect evidence, but also because all the (potentially) drought-related information comes entirely from legal-administrative documentation, charters and (official) letters. References on possible dry spells occasionally, ‘randomly’ appear in charters, and can equally reflect on ‘simple’ dry spells or more significant drought events, while even outstanding droughts remained unrecorded. Even more indirect evidence is harvest and market-price reports and food-shortage data in years without other destructive extremes (e.g. plague, late frosts, hard/long winters).

Apart from the legal documentation where, in most cases, only the terminus-post-quem dating of a weather-related event, dry spell or drought is known, many of the cases – discussed in the present paper – refer to perambulations, field surveys, where the exact date, the name and location of the landed possession and, within that,

According to the OWDA, in (spring-)summer 1371 there was drought in Western and West-Central Europe, and in the western part of the Carpathian Basin were also dry or very dry (Fig. 2). Similar picture is presented in the documentary evidence available from then neighbouring countries and Central Europe: the May was very dry in Bohemia with frequent fires, but already the winter was quite mild, just like in Mainz, where the summer was described as very dry (Alexandre, 1987; Brázdil and Kotyza, 1995). There was great drought in Piacenza, Florence and the entire Toscana, with many “*pro pluvia*” processions in mid-/late August, and a lightning struck the church spire in Posnan (Malewicz, 1980; Alexandre, 1987). In this year, similarly mild winter and drought were reported in Russian sources (Klimenko and Solomina, 2010).

Temporary watermill stops working: January 1375

On 8 (GC: 17) January 1375 a land and property survey took place, amongst others, in *Berench* (Rétközberencs) along the River Tisza, in the Great Hungarian Plain, today in North-eastern Hungary (HNA DL 96492/1,2; Piti, 2010; see also: Vajda, 2012). While listing the properties of the village, a watermill was mentioned that operated over a waterflow in times of flooding. However, because of the lack of water, it did not work in the time of the property survey. The survey also affected other landed possessions in the neighbourhood: a dried-up ditch with three weirs is described in the area of *Monoros* (Tiszamogyorós), similarly located in the Rétköz, the floodplain area of the Upper-Tisza. The charter also reported on dry mills in the surveyed areas where, instead of water, animals were used for energy supply: one of these dry mills was located in *Berench*.

Before the mid-/late 19th-century river regulation works, this low lying area along the Tisza was prone to floods, and the village was surrounded by wetlands that

usually provided high protection against unwanted visitors. Examples of significant flood events were also reported in the Rétköz area in the mid-/late 14th century, in 1342, 1345 and 1381 (Kiss 2019a). The watercourses of this area are under the influence of the River Tisza, whose lowest water levels usually occur in mid-/late summer and early autumn, and medium (but not low) water levels are typical in January (Lászlóffy, 1982). Thus, the report does not necessarily reflect on a drought. Nevertheless, as winter high waters/floods were not unusual in this area, and the ditch/watercourse in the neighbourhood, used for fishing, was also dry, we can still state that dry conditions prevailed around and before mid-January in this year. This is also interesting, because just a year earlier, due to exceptionally abundant winter rainfall, the winter-spring of 1374 became famous of great floods in Europe (e.g. Alexandre 1987; Kiss 2019a). Winter floods also affected Hungary, even if probably the contemporary source referred primarily to the Danube area (see Kiss, 2019a).

Regarding the weather conditions of the neighbouring countries, no information is currently available from the winter of 1374 and 1375 in the Czech Lands, Poland, Austria, Germany and the Byzantine Empire (Malewicz, 1980; Rohr, 2007; Telelis, 2008; Glaser, 2013). However, great drought was reported in Liège and Mainz in later spring and summer (Alexandre, 1987), and droughts were documented in Russia in the mid-1370s (Klimenko and Solomina, 2010). Although the differences in climate mechanism make any relationship occasional and somewhat indirect between the two catchments and regions, it is still worth mentioning that low Nile floods were reported by Byzantine sources in both 1374 and 1375 (Telelis, 2008).

As our study area is located in the north-eastern part of the Great Hungarian Plain, and in the north-eastern part of the Carpathian Basin the influence of the hydroclimatic

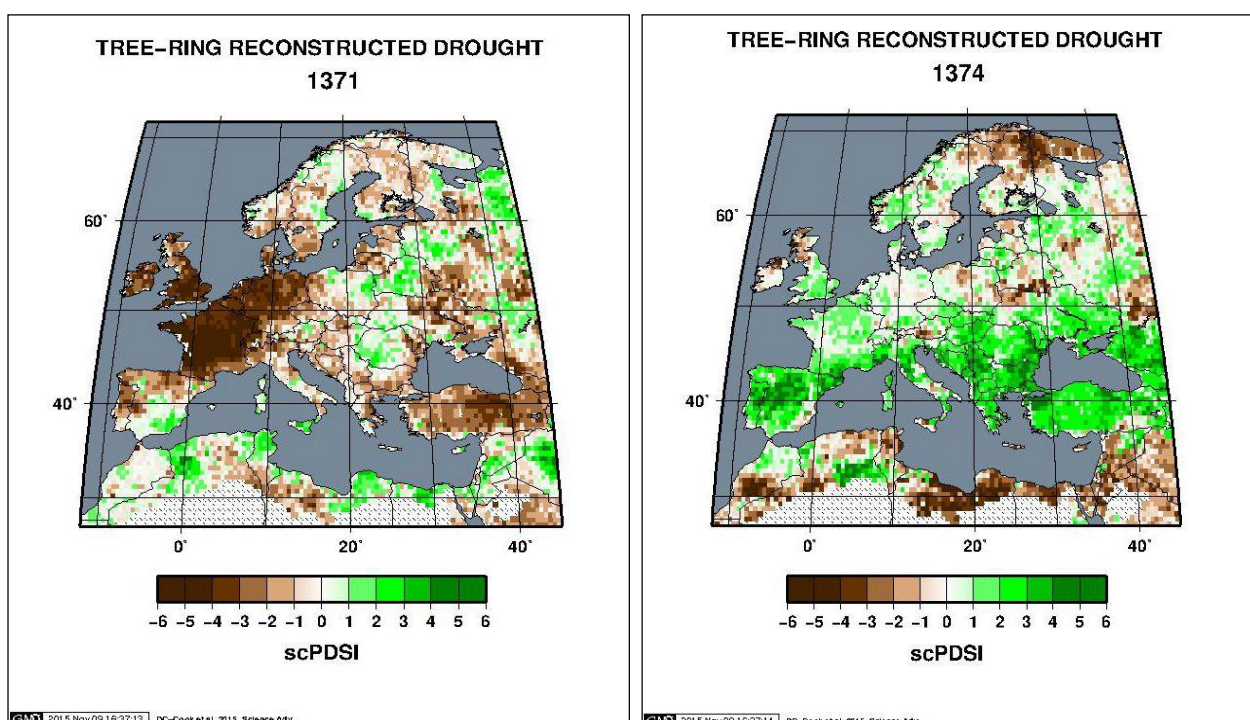


Fig. 2 The OWDA reconstruction for the years 1371 and 1374 (Cook et al., 2015; Old World Drought Atlas Data on NOAA)

influence of the regions north-east to the Carpathian Basin are also relevant, it is possible that – similar to the situation in the Eastern European Plain – overall dry conditions prevailed in the mid-1370s, and also in winter 1475. However, based on the available data, regarding our case study, we can only conclude that a dry spell was observed and described in the Rétköz area in January 1475.

As for the north-eastern parts of the Carpathian Basin, both in 1374 and 1375, the OWDA shows overall somewhat different, drier patterns compared to the rather wet conditions in most of the Basin in these two years (see Fig. 2). There is also a tendency from wetter (1374) to drier (1375) conditions in these years. Moreover, the summer and winter half years could have rather different precipitation and hydroclimatic patterns within the same year.

Water body dried up due to great drought: spring 1378

The location of the next report is east, north-east from the January 1375 report, in the north-eastern part of the Great Hungarian Plain, between the Szamos and the Tisza, but nearer to the River Szamos, in an area criss-crossed by many watercourses, dependent on the water supply of the two main rivers. Related to a debate over the ownership of *Chazlou* (Császló) landed possession, a perambulation took place on 31 March (GC: 9 April; see Fig. 1). During this field survey (Nagy et al., 1878), the perambulators also described the properties that belonged to the landed possession, and noted that the local water body dried up in time of great drought, as this water body did not receive water from other water bodies (called “*er[d]*”), as they found it there (“...., *et aqua, que tempore siccitatis magne ex eo, quia deriuaciones ab alys aquis Erd dictis ad se faciendas non habent, solent exsiccati, in facie ipsius possessionis reperissent*”).

Although mentioned in general, the text rather describes the (great) drought as a condition what the perambulators experienced during the field survey. Before the 19th-century water regulation works, this area was criss-crossed by smaller and larger water channels. The desiccation of a (stagnant) water body, having no direct only indirect connection to the main rivers, still required low groundwater-level conditions in this area, and since groundwater levels are dependent on the water-level conditions of the Rivers Szamos and Tisza, the drying up of a stagnant water body indirectly reflects on the low water-level conditions of the two major rivers of the region.

For the North-eastern Great Hungarian Plain, and particularly for the region where Császló is located near the River Szamos, the OWDA suggests moderate dry conditions for the (spring-)summer period of 1378. Nonetheless, in the areas east, north-east to the Carpathian Basin, especially in the territories of today’s Ukraine, the OWDA suggests a significant drought for this summer (Fig. 3). Furthermore, in both 1377 and 1379 the OWDA presents significant droughts (Fig. 3; Cook et al., 2015). However, the dating of the charter is clear, and also the course of the legal debate makes the 1378 dating unambiguous. As the field survey took place in early/mid-spring, it is rather possible that still the water-deficit conditions of the previous year continued in this area, and the charter in fact largely also reflect on the problems started at least in 1377.

Based on documentary evidence from the neighbouring countries and (Central) Europe, in Austria, the Czech Lands and Poland, no information is available regarding 1378, but in (late spring) 1379 there was great drought, the ditches were dry in Pomerania (NW-Poland); Miechów and Radomska towns burnt down and there was

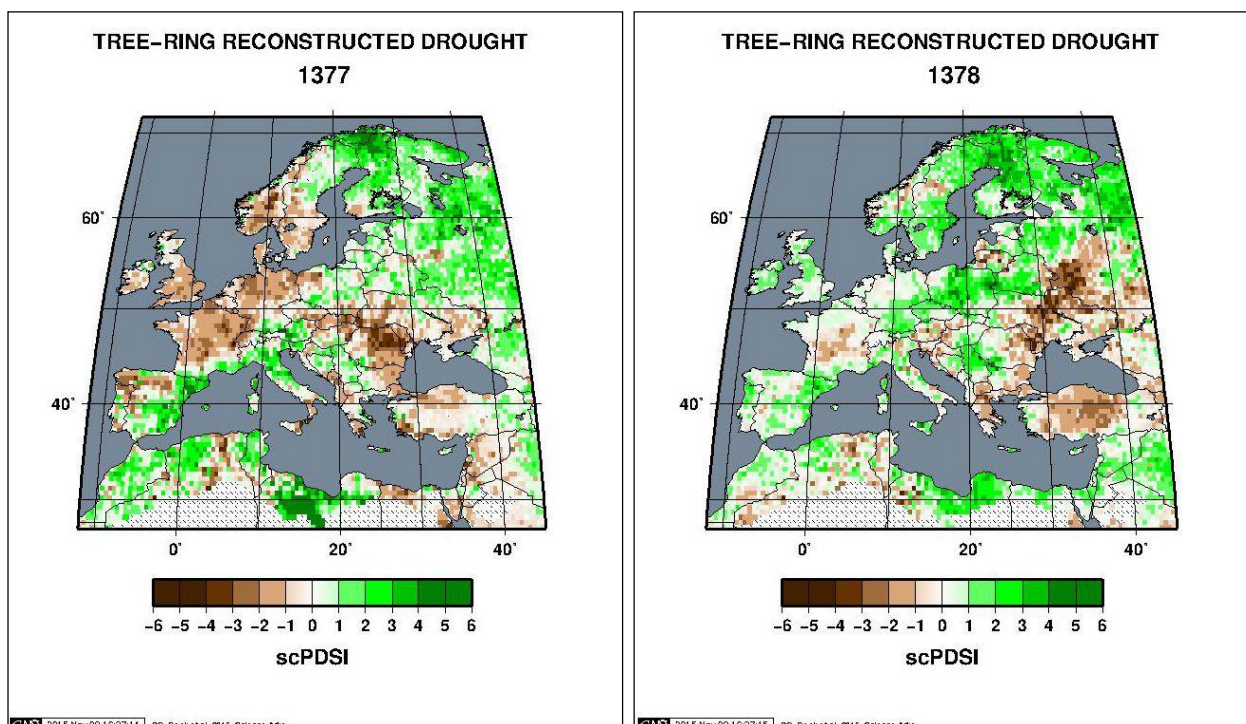


Fig. 3 The OWDA reconstruction for the years 1377 and 1378 (Cook et al., 2015; Old World Drought Atlas Data on NOAA)

great (summer) drought in the kingdom of Poland (Malewicz, 1980). While no weather-related evidence is available from the Balkan area regarding 1378, the high level of watercourses was reported in mid-April in the Arnhem area (E-Netherlands), and in late March the abundance of snow was reported in Vicenza, North-eastern Italy that stayed for a longer period (Alexandre, 1987). Beyond that, only the early March great frost at the Bodensee is known from the year (Alexandre, 1987; Glaser, 2013).

Potential signs of the 1393 drought in medieval Hungary

In 1393 great drought was described by a number of contemporary sources in Central and Western Europe (e.g. Alexandre, 1987; Brázdil and Kotyza, 1995; Rohr, 2007; Glaser, 2013). Moreover, both based on documentary and the OWDA evidence, approximately in the same regions of Europe as in 1393, the drought continued in 1394 (see Fig. 4), while the Nile – just like in 1374 and 1375 – also had low flood in this year (Telesis, 2008). Contemporary charter evidence may also provide indirect parallels in the Carpathian Basin to this great drought event, even if the tree-ring based hydroclimate reconstruction of the OWDA only suggested drought in the western, north-western and the most north-easterly parts of the Carpathian Basin for this year. No direct contemporary reference is available in medieval Hungary that would mention this drought. However, some indirect evidence may increase the chance that this drought affected larger areas in (Western?) Hungary, too.

An early harvest reference is available from March 1394, dating the illegal harvesting of grapevine prior to 8 (GC: 17) September 1393 in Kál, north to Lake Balaton, in the Central Transdanubia (HNA DF 200361; Kiss, 2016). Although this is primarily a temperature-related information, great droughts are usually accompanied by higher temperature values and earlier harvests (see e.g. Wetter et al., 2014; Kiss, 2018; Camenisch et al., 2019).

In November 1393, a court hearing took place: the abbot of the monastery of Elefánt (Lefantovce-Sk) blamed the noble neighbours for causing water deficit to the watermills of the monastery with diverting the course of the mill canal of the River Nitra (HNA DL, 7902; Mályusz, 1951). Although the abbot presented as a fact that the water was diverted, as no further part of the legal debate is known, it is not possible to decide whether the abbot was right in blaming the neighbour, and in what extent the neighbour can be blamed for the water deficit. However, in another case, in 1422, when the abbot blamed neighbouring landowners with causing destruction in the mill of the monastery, the damage was caused by the vehement flux of the river and not by human intervention (see Kiss, 2019a).

A further case concerns the Danube in 1393: similarly in November, a charter was issued containing the complains of the parish priest of *Pispuky* (Püspöki; today in Bratislava-Sk), referring to an island that changed location due to previous floods. Situated closer to *Orozwar* (Oroszvár; today part of Bratislava-Sk), the serfs of the latter domain started exploiting (illegally) the forest on the island (HNA DF, 237891; Mályusz, 1951; see also Kiss, 2019a). As usually it was easier to exploit island forests and especially to transport the wood from the island areas, in times of low water levels, it is possible that the water level of the Danube was low for a longer period in this year, providing suitable conditions for the illegal woodcutters. This is especially likely, as there was great drought in Austria in 1393 (Rohr, 2007).

On 28 June (GC: 7 July) 1394 a perambulation took place in Baranya County, in the area of today's Majs, (Nagy)Nyárád and Kölked, between the lands of the local landlord, László Töttös and the cardinal-bishop of Pécs. During the field survey and perambulation between *Laak*, *Laymer*, *Kerekyghaz* and *Maysa* landed possessions, the survey proceeded from *Lak* towards the west, along the

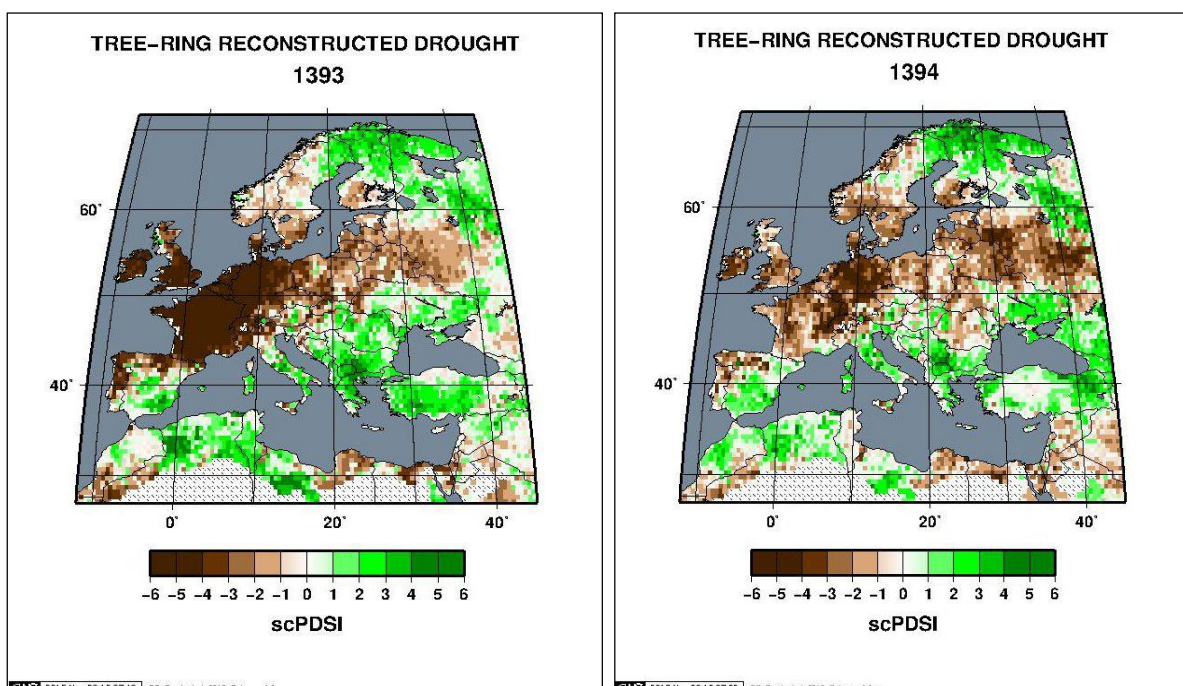


Fig. 4 The OWDA reconstruction for the years 1393 and 1394 (Cook et al., 2015; Old World Drought Atlas Data on NOAA)

big (main course of the) Danube, reached the place where the small Danube (a Danube branch) left the big Danube; here, just along the river and its branch, the charter described a dry meadow (Nagy, 1878). Taking into consideration the moderate elevation differences and low elevation conditions of the area, the mentioning of a dry meadow right along the main Danube and its branch is rather interesting, as the area is under the direct hydrological influence of the Danube.

It is also interesting that in 1395 an Italian delegate – staying in Buda and sending regular reports on his 'observations' in the royal court, the town and the country – asked his lord, the Duke of Mantua, for permission to return to Italy, because his spendings were too high, caused by the current high prices in the town (Óváry, 1890; see also: Kiss et al., 2016). Although little is known about the weather conditions and harvest results in 1394, the high prices on 27 November (GC: 6 December) 1395 might be still related to the great drought, especially because, according to the OWDA, there was also significant drought in 1394 in large parts of Western, Central and even in Eastern Europe, but drought continued in the German areas, Eastern Europe, and also in Transylvania and the Balkan in 1395 (Cook et al., 2015). However, the OWDA does not list most of the Carpathian Basin among the affected areas.

Based on the OWDA, however, the (spring-)summer drought in 1394 only affected Transylvania and the north, north-eastern (hilly) areas of the Carpathian Basin. Although the reconstruction also suggests conditions somewhat drier than usual in the western part of the country, including the Little Hungarian Plain (Kisalföld), which was the main crop supplier of Buda in the late Middle Ages (Kubinyi, 1975), this general water deficit does not reach the extent of a drought in the OWDA reconstruction (see Fig. 4). Nevertheless, if this moderate dry (spring-)summer arrived after a much drier year, theoretically the somewhat better conditions (and harvest results) could be still insufficient to provide enough food-crops to feed the entire town and its agglomeration.

In conclusion, a number of indirect evidence suggest that the 1393, and possibly also the 1394, European droughts had some impacts in Hungary, too. The indirect evidence, on the one hand, refers to the contemporary potentially low water-level conditions of the Danube, reflecting on the great (hydrological) drought that affected the German areas and Austria in 1393. On the other hand, all other – potentially drought-related – information comes from the western, north-western part of the Carpathian Basin, where otherwise the OWDA also suggests a (moderate) drought for this year. It is not clear whether the high prices, mentioned by an Italian delegate in 1395, are still related to this drought, however, except for most of the Mediterranean, 1394 was also a drought year in most parts of Europe.

1415-1416: problematic years – full of contradictions?

In connection with a postponed legal debate in 1415, very high prices or dearth of the recent past, that had already passed, were mentioned on 30 July (GC: 8 August) in Doboka County, Transylvania (HNA DL 73953; Mályusz, 1997, see also Fig. 1). As the information comes from around harvest time, most probably the bad harvest

of the previous year or years was followed in 1415 by a better one, so that the crisis was over with the new harvest.

Dated to 6 June (GC: 15 June) in the same year, a royal order (of King Sigismund) was issued in support of the parish priest of Szentpéter (today part of Cluj-Napoca-Ro), related to a mill whose utilities belonged to the parish, but the neighbouring Kolozsvár (Cluj-Napoca-Ro) town questioned this right (Jakab, 1870). There is a rather interesting sentence in this charter, stating that the serfs of the parish, in their grave poverty – as heaven took away their resources –, could not afford a coach to carry their crop harvest to the mill, and therefore for them this mill was of highest importance, as they would have been unable to travel to another, distant mill. This sentence – possibly reflecting on multiannual problems – might be particularly interesting, when we take into consideration that the parish was located in one of the richer, central parts of Transylvania. However, the situation probably becomes more understandable when taking into consideration the previous evidence on great dearth, also coming from Transylvania.

Similar problems were recorded in the next year: on 6 October 1416, Queen Barbara/Borbála (wife of king Sigismund) ordered Sopron County officials to prohibit the export of cereals (Házi, 1923). The prohibition of cereal export had been previously decided, because the king wanted to avoid the further increase of the countrywide high prices/dearth ("*caristia non modicum*"), indirectly suggesting larger-scale problems within the country.

Hardly more than a month before, on 3 (GC: 12) September 1416, a high officer of the Austrian prince sent an official letter to the town council of Sopron asking for the reason of prohibiting the export of oat to Austria (Házi, 1923). As Vienna in the late 15th century largely depended on grain import from the Czech areas and Hungary, the prohibition most probably caused shortage in resources. Moreover, the document indirectly also suggests that the royal order for prohibiting cereal export was most probably dated not much earlier, perhaps to (late?) summer, possibly responding on an overall weak harvest, and a (reasonable) fear of a(n even graver) dearth in Hungary. However, it is interesting that, despite the intensive daily trade connection, the Austrian court had no knowledge of the reasons of prohibition in Hungary. This circumstance may indirectly suggest that in the Sopron area and at the western borders of the country there was no bad harvest or significant shortage of cereals (oats in specific) in this year.

The reports on very high prices and/or great dearth in Transylvania in 1415 and then in the entire country in 1416 altogether suggest significant problems with harvests on a multiannual scale in 1415, 1416 and most probably also, at least, in 1414. As large-scale (crop) harvest problems in the country are usually the consequence of prolonged dry conditions, and sometimes also of extreme hard winter, late frosts or, even more rarely, the too much precipitation, it is rather important in finding possible explanations that, based on the OWDA, drier than usual conditions prevailed in 1414 and 1415, while 1416 was dry in the north-west, but in the rest of the country average or slightly wetter conditions were dominant (see Fig. 5).

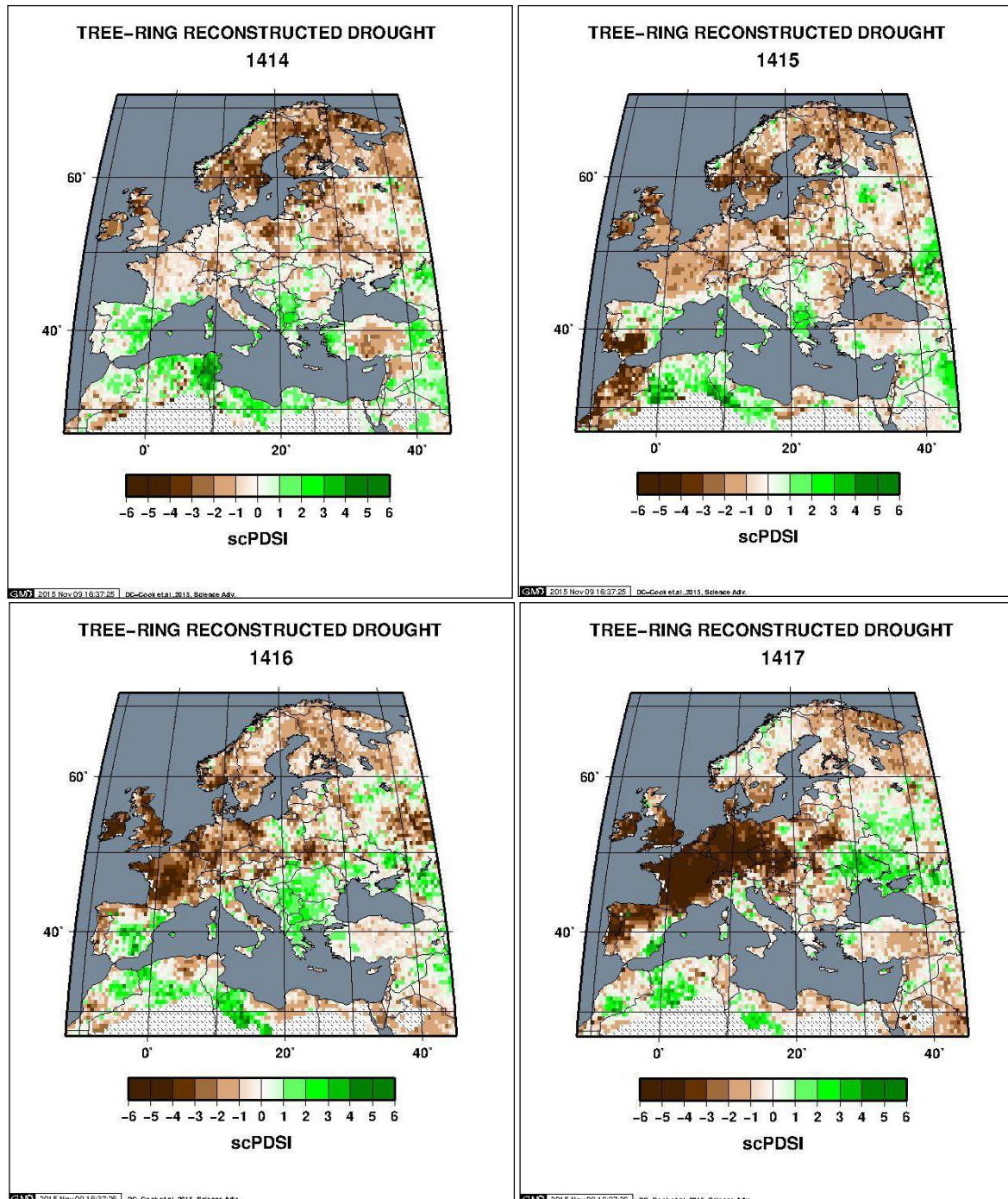


Fig. 5 The OWDA reconstruction for the years 1414–1417 (Cook et al., 2015; Old World Drought Atlas Data on NOAA)

Thus, the OWDA does not suggest for the Carpathian Basin strong drought for 1414, 1415, and in 1416 only the western, north-western part of the Carpathian Basin was dry, while the rest of the country was more wet than dry. Around average or moderately wet conditions, in themselves, are usually favourable for agriculture in the central and eastern parts of the country; apart from the temperature extremes, only very/prolonged dry and rarely prolonged very wet conditions cause problems. Furthermore, a mid-July Danube flood and a winter flood in the north-east, in the Upper-Tisza catchment was recorded in January 1416, whereas practically no ongoing floods of Carpathian Basin origin were documented in 1414–1415 (see Kiss, 2019a).

The situation what we gain from the documentary evidence of the neighbouring countries is even more complex, partly also contradictory. In Poland, for example, documentary evidence suggests rains in summer 1414, and the whole year was rather wet in 1415 (Malewicz, 1980), while for both (spring-)summers the OWDA suggests notable dry conditions (Fig. 5). Rainy summer was suggested for 1415 in Bohemia (Brázdil and Kotyza, 1995) – the OWDA suggests considerable dry conditions for the same period (Fig. 5). In Austria, summer was rather warm in 1414, but 1415 was most probably also wet (Alexandre, 1987).

The picture is similarly contradictory in other parts of Western and (Central) Europe. Based on Glaser (2013), in the German areas, after the hot and dry summer of 1414 and

the presumably average summer, no information is available regarding summers (or other seasons) until 1418. Alexandre (1987) suggests that, after the summer droughts in 1412–1414, spring-summer of 1415 was wet with inundations, floods were also reported in June-early/mid-July in 1416 in the westernmost parts of the German and the eastern parts of French territories. These descriptions clearly contradict with the OWDA reconstruction (see Fig. 5), where notable drought is presented in the same areas. (Northern) Poland was similarly wet in summer 1414 and in 1415 (Malewicz, 1980) – but, at least, in case of Poland the OWDA also suggests wetter conditions. On the other hand, in 1416 great heat and drought was described between mid-August and early October in Forlì and Sienna, in Italy. Usually collected in (late June)-July, such a late-summer drought would not have affected the crop harvest in Hungary.

Thus, 1414 might have been problematic because of dry and hot weather, while in case of 1415 documentary evidence suggest wet, while the OWDA suggests dry conditions for (spring) summer 1415 and 1416 (see Fig. 5). Winters were average, cold in some parts in Bohemia and the German areas (Brázdil and Kotyza, 1995; Glaser, 2013).

In general, the 1415–1416 cases provide a rather contradictory picture. The 1415 Transylvanian reports, well before harvest time, mainly refers to problems of the previous years, especially to the dry period of 1412–1414. In 1415 and 1516, the shortage of crops inducing export prohibition might have been partly or mostly due to extraordinary wet conditions in the central and eastern parts of the Carpathian Basin. This might be also supported by an application from the western edges of Szatmár County, generally complaining on the many floods (of the preceding times), caused by the abundant multiplication of rains prior to 1417 (see Kiss 2019a). However, considering the rather contradictory, opposite patterns – presented by documentary and the OWDA reconstruction – we cannot completely exclude the possibility that also in 1415 and 1416 dry (and or cold) conditions prevailed in the first, most important spring part of the vegetation period in the central and eastern parts of the country that badly affected harvests in these years.

1417: drought or not?

The charter of the St. Stephan order in Székesfehérvár, issued on 25 December 1417 (GC: 4 January 1418), states that their *Zedregh* landed possession often lacks water in summer (“*Ceterum quia tempore estivali sepius aqua in ipsa possessione deficeret*”), and when it happens, the other owner is obliged to provide ample water supply to the other landowner, his serfs and animals (HNA DL 105344; see also Mályusz and Borsa, 1999). According to Fejér (1844b), the landed possession, with settlement, was located in the southern part of Fejér County, between The River Sárvíz/Sió and the Danube, in the area what is today Előszállás, Alsószentiván and Nagykarácsony (see Fig. 1). The landed possession was located in a sandy wetland area, and was clearly populated at the time of the charter issue, and at least one notable local noble family also lived there. Moreover, another charter of the same survey is available from the (same) December 1417 survey (HNA DL 43377) – yet without mentioning the water deficit problem.

As the charter specifically states the summer water deficit problem, and therefore the problems has great importance for the landed possession, it is rather possible that the summer water deficit mention reflects on current (or near-past and/or multiannual) problems. The OWDA suggests significant drought for Western and Central Europe for (spring-)summer 1417. With particular intensity in the north-west, based on the OWDA, in 1417 there was also drought in the Carpathian Basin. Moreover, based merely on the OWDA, in the western part of the country dry or rather dry (spring-) conditions prevailed in each summer already from 1407 (see Fig. 5).

As for the documentary evidence in other parts of Central Europe, the winter of 1417 was memorably hard and rich in snow: both Austrian, Czech and German sources speak about the severity of this winter. In general, from Liguria through Germany to Poland, the very cold (and snowy) character of the winter was emphasised in 1417 (Malewicz, 1980; Alexandre, 1987; Brázdil and Kotyza, 1995; Glaser, 2013). In Poland the winter was so cold that crops were destroyed, and – as summer was also unfavourable for crop development – there was bad cereal harvest (Malewicz, 1980). Although the source does not describe summer conditions any further, one possibility for the cause of bad harvest might be (spring-)summer drought.

No information on this summer is available from the Czech Lands regarding the year 1417 (Brázdil and Kotyza, 1995). In Austria, the cold and snowy winter, when the Danube also got frozen, was followed by good vintage and good quality of wine that suggests warmer than average summer conditions (Alexandre, 1987). Moreover, good harvest may also suggest that, despite the hardness of winter, the winter frost did not severely damage the vinestocks (or the snowcover was thick enough).

Famine in mid-/late 1420s: any relationship to drought?

On 19 October 1428, King Sigismund gave some tax relief and further privileges to the Iasonians, because of the dearth or famine affecting them for years (*propter caristiam sive famem aliquorum annorum, post sese continuo praeteritorum*; see Fejér 1844a). Documented in mid-February 1428, most probably in the previous year the town of Nagyszőlős (Vynohradiv-Ua) in Ugocsa County, in the north-east, partly burnt down (HNA DL 70845, see Fig. 1).

In the Middle Ages, Iasonians lived in one block in Iasonia, mainly around the present-day Jászberény and Jászfényszaru towns, but also lived scattered in various regions, partly east, south-east to Pest (e.g. Cinkota; today part of Budapest), and partly along the River Tisza in the Great Hungarian Plain. Although, similar to Cumans, their main activity was animal husbandry, they were traditionally more involved (than Cumans) in land cultivation, too. The multiannual famine among the Iasonians clearly had to be, at least partly, related to unfavourable weather conditions, a circumstance that hit their traditional economy for a longer period of time. Thus, it was most probably not (only) the result of a single hard winter, late frost or any other, individual extreme event. Furthermore, as Iasonians mainly lived in the floodplains of the drought-sensitive Great Hungarian Plain, their agricultural activities strongly depended on the availability of water.

The fire incident in Nagyszőlős (today Vynohradiv in the Transcarpathian region of Ukraine) occurred in an unknown time, but not immediately before mid-February (i.e. more probably in 1427), and not the entire town but only part of it burnt down. As large scale fire events favour dry and windy conditions, in such a case there is a higher likelihood that prolonged dry and windy conditions were also responsible for the calamity. However, we have to add that chances for devastating incidental fires are also higher in hard winters and prolonged hot (and windy) conditions. Thus, drought is not necessarily a precondition.

Although rather indirectly, it might be also important that, after the autumn 1424 River Nitra flood, no ongoing floods of Carpathian Basin origin are known from contemporary documentation until 1432 (see Kiss 2019a). Naturally, the lack of flood-related documents does not mean the complete lack of considerable or even great flood in a year. Nevertheless, when less unusual floods occur for multiple years then there is more chance that floods remain unreported, and in case of a longer period without flood evidence the likelihood for generally drier conditions is higher (but not exclusively) than in other periods.

For 1427 and the years before, the OWDA suggests dry or very dry conditions. In fact, rather dry conditions prevailed in each year from 1417 until 1427; based on the OWDA, the first wetter year was 1428 (see Fig. 6). Thus, it is rather possible that the prolonged dry conditions (11 years!) had major responsibility in the multiannual food shortage problems described in the charters. Moreover, based on a royal charter, the winter of 1427 was rather (or even: exceptionally?) cold and snowy in Transylvania, when Turkish troops broke into the country and caused immense damages (Fejér, 1844a). Combined with the multiannual drought, hard winter conditions might have meant an additional stress and could increase the food supply problems.

The ‘perfect match’ in the year of Reformation: the great drought of (1516-)1517

Based on the OWDA hydroclimate reconstruction, in the year of the Reformation (Luther’s proclamation to the bishop of Mainz: 31 October, 1517), an outstanding drought occurred in (spring-)summer all over Central and Western Europe, and already 1516 was a drought year in Europe (see Fig. 7). This reconstruction is in ‘perfect match’ with the information derived from documentary sources: both in direct and indirect evidence, this drought was also documented in contemporary sources in the Carpathian Basin.

In a royal order written on 19 (GC: 29) August 1517, the king ordered all judges, lay or ecclesiastical, first to suspend for 15 days and then to completely stop all legal procedures in the kingdoms of the Hungarian crown in which the Duke of Slavonia, Ferenc Hédervári, and his vassals (so-called “*familiares*”) were involved, as they were at that time occupied by the defence against a threatening Turkish attack in the two most endangered counties, Valkó (Vuka-Hr) and Pozsega (Požega-Hr), in Hungary and Slavonia (HNA DL 91054; see also Fig. 1).

The fact that the two counties, located along the lower sections of the River Sava, were most in danger reflects on the one hand the location of the Turkish strongholds, but also suggests prolonged critical water shortage in the entire catchment area of the river, not only in the south-eastern part of the Alps and Slavonia, but also in Bosnia. As a potential parallel, extreme low Sava water level was mentioned in 1474: at that time it was related to an outstanding great drought, affecting the Carpathian Basin and the South-eastern Alpine area, both in 1473 and 1474 (Kiss and Nikolić, 2015; Kiss, 2017). The similarities in conditions may raise the possibility that the drought probably started already in 1516.

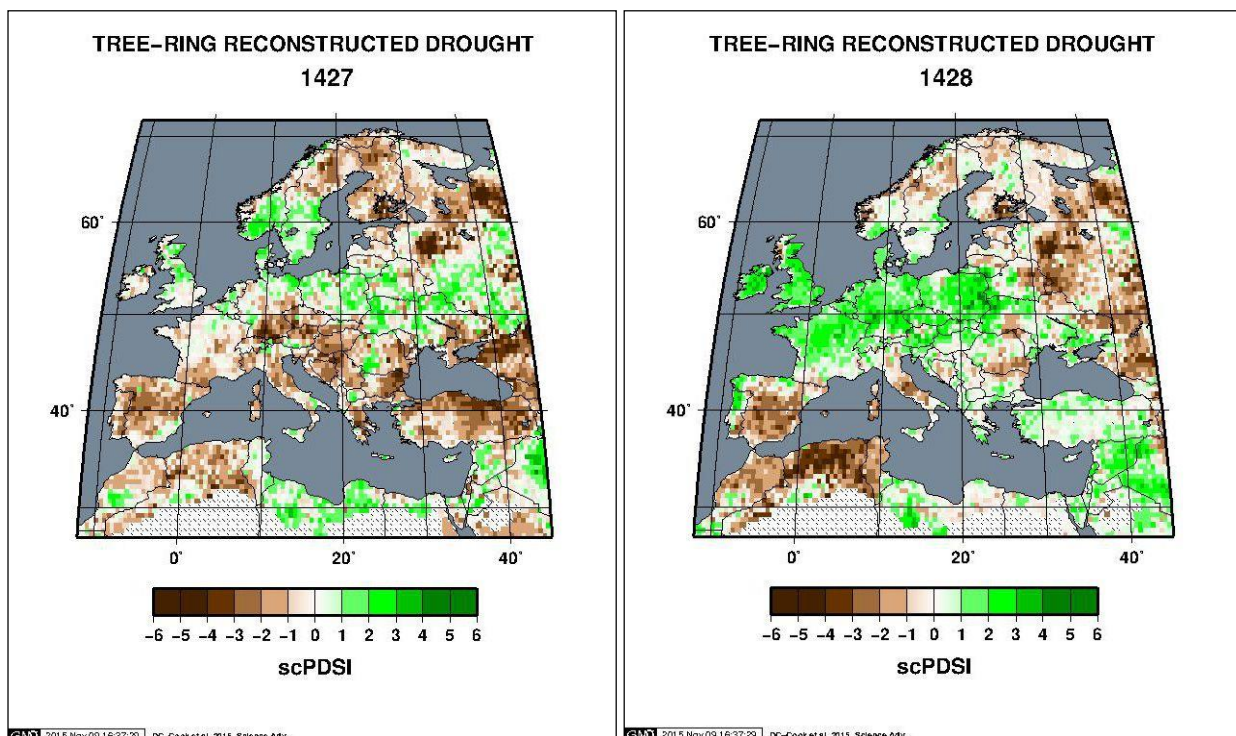


Fig. 6 The OWDA reconstruction for the years 1427 and 1428 (Cook et al., 2015; Old World Drought Atlas Data on NOAA)

Another report, indirectly reflecting on drought and unfavourable weather conditions, also suggests that significant anomalies occurred in 1517 and possibly also in early 1518. On 17 (GC: 27) April 1518, a letter was sent by the town officials of Nürnberg to the nearby Rosenberg, providing an explanation on the current high prices of meat in the German areas. According to the letter, the problem originated in Hungary: lacking fodder in winter, large part of the cattle perished that caused a shortage of meat in the German areas (Thallóczy, 1900).

Mass loss of cattle in Hungary was usually related to bad hay harvest, which was predominantly the consequence of drought. However, fodder shortage – resulting mainly the loss of young animals – might have also developed during prolonged hard winters. A multiannual drought, alone in itself, or the combination of a drought and then long hard winter could have catastrophic consequences on the cattle population.

A further, indirect evidence also suggests considerable problems: on 30 May 1517, the lead tax officer sent a report to the Duke of Slavonia and Croatia, stating that it was not possible to gather taxes from his Slavonian serfs due to their extreme poverty that was so great that many died in famine (Iványi, 1942; see also Kiss, 2019b).

Apart from the drought both in 1516 and 1517, winters of both years were, at least partly, also severe. Nevertheless, the selling and production prices, recorded in the Tokaj-Hegyalja Wine Region (in Tállya; see Gecsényi, 1966), were relatively low and decreasing in both years, indirectly suggesting that the winters of these two years were not hard enough to have multiannual negative impacts on the vinestocks and wine production.

Already the summer and autumn of 1516 was very dry, but after a hard and moist winter, the spring of 1517 was again unusually warm, and extreme dry – the

driest of the century in the German areas. Heavy frost that caused great damage in the cultivated vegetation was followed by very hot and dry summer, also reflected in bad hay harvest results. However, the second decade of July brought rain and, according to Glaser (2013), rainy weather continued in August and much of September in the German areas. The winter of 1518 was suggested to be altogether normal, but with great regional differences (Glaser, 2013).

The very hot and dry character of summer 1516 is also emphasised in Bohemian sources, and in fact – just like in Poland – the entire year was dry with low water levels of the River Elbe (Brázdil et al., 2013).

DISCUSSION

(1516-)1517: comparable to the most severe droughts of 1473(-1474) and 1540?

In France, Le Roy Ladurie (2004) referred to the 1517 drought as comparable, or even more severe, than the one in 1473, also legendary in Hungary (see Kiss and Nikolić, 2015; Kiss, 2017). For the Carpathian Basin, the OWDA suggests lower PDSI index values for 1517 than for 1473 or even for the other outstanding drought, 1540 (see Fig. 8).

Based on the information available in documentary evidence, it is difficult to decide over the differences in the magnitude of the drought events – all three were important, but for 1473-1474 and 1516-1517 we have more direct contemporary evidence that refer to outstanding drought. In Hungary, we have no information about broad-scale food or fodder supply crisis in 1473-1474, but both in 1516-1517 and after 1540 there were significant problems documented. Both in 1474 and 1517 low water-level problems were recorded. However, only in one case, in 1517 mass perdition of cattle was reported. Based on this latter information,

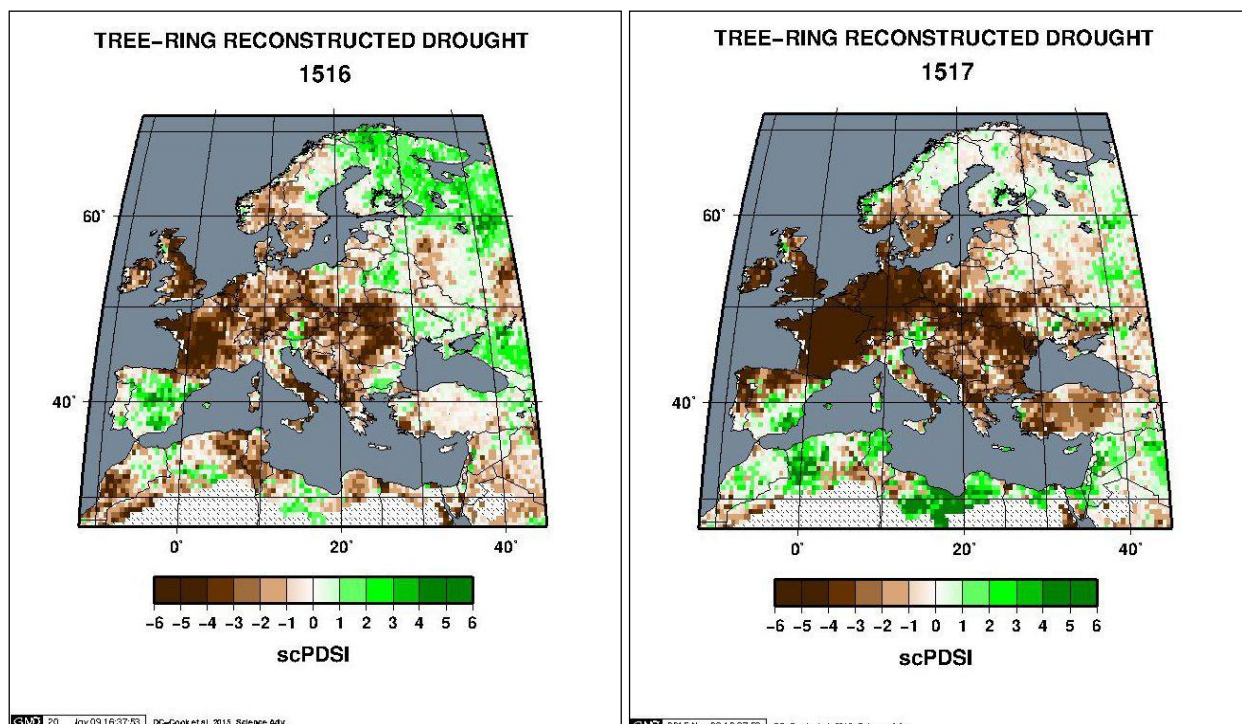


Fig. 7 The OWDA reconstruction for the years 1516 and 1517 (Cook et al., 2015; Old World Drought Atlas Data on NOAA)

probably the (1516-)1517 drought holds the most signs of an outstanding drought – this drought was also singled out as most extreme between 1450 and 1550. However, the evaluation strongly depends also on source availability.

Another, rather thought-provoking circumstance is the potential relationship between the great drought of 1517 and the previous years and the start of the Reformation. Even if the reasons for the reformation rooted in societal problems and the (moral, structural) crisis of the church, the increasing societal and economic tension within the society, caused by bad harvests due to unfavourable weather conditions, and the recurrent significant and outstanding droughts in particular, provided a favourable background to the increasing desire in the lower layers of society for considerable changes. In the earlier part of the decade (i.e. 1513-1514) this increased societal tension manifested itself in peasant revolts that affected much of Central Europe including Austria, German territories in the south, south-west as well as the Hungarian kingdom (see Kiss 2019b). Thus, even if no direct relationship can be detected between multiannual dry conditions, droughts, societal tension and abrupt changes, multiannual dry conditions were partly or mainly responsible for repeated bad harvests that could be an important contributing factor, a catalyst of societal changes. No such substantial, abrupt changes can be detected in the 1470s and around 1540, which fact also reflects on the primary importance of (long-term) socio-economic processes over the importance and influence of multiannual unfavourable weather conditions.

Potential, indirect references on droughts or dry spells

Several types of potential, indirect indicators of dry spells or drought were already listed in this and the previous papers of the series. In this subchapter a short overview of these indicators, and some additional further indicators are discussed in brief. It is important to note that most of the

listed cases or problem groups did not only occur during dry spells or droughts; however, we argue that the frequency of these problems – and therefore the likelihood for documentation – is often, but not necessarily, higher than in other years. The list presented here is not exclusive – further indirect indicators may be suggested later, in due course.

Potential signs of large-scale harvest problems – often induced by prolonged dry spells or drought – could be, for example, the increased number of controversies, violence, illegal gathering or confiscation (robbery) of hay or crop harvest and the similarly illegal (crop) cultivation of other people's meadows. More hay-related problems such as robbery, violence against harvesting peasants or land-usurpation were documented in charters, for example, in 1473, 1479-1480, 1494, 1503, 1506-1507, the early 1510s or in the late 1510s and early/mid-1520s.

Based on the abstract search in the charter abstracts of the medieval collection of the Hungarian National Archives, for the period 1300-1526, currently we found 107 years when hay-related problems, negotiations, illegal acts (violent attacks, illegal activity, meadow occupation etc.) were mentioned in legal documentation at least once a year (sources: Hungaricana database). Out of these 107 years, the OWDA suggested drought or severe drought in case of 44 years, while notable dry conditions, dry spells were in 21 years. In case of other 40 years no significant dry conditions were presented by the OWDA, and only in two cases hay-related controversy was mentioned in particularly wet years. Thus, this means that in 2/3 of the hay-problem cases notable dry conditions or droughts were captured by the OWDA for the (spring-)summer period. However, it is important to emphasise that the relationship between dry conditions and hay-related controversies is far not exclusive: sometimes even in particularly wet years we can meet with such problems. Still, there is a higher likelihood for the occurrence of such problems in dry years.

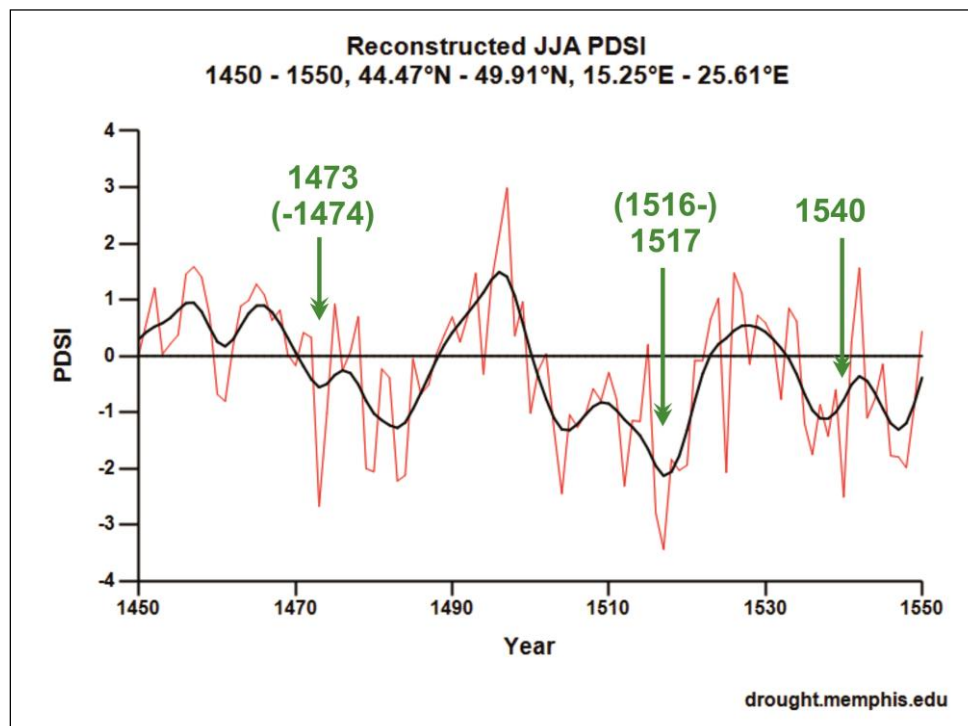


Fig. 8 The OWDA reconstruction for the years 1516 and 1517 (Cook et al., 2015; Tree Ring Drought Atlas Portal)

Rather similar results can be gathered from the same late-medieval database regarding crop-related controversies, violence and the illegal gathering of crop harvest. Based on the OWDA, out of the documented 56 years, the (spring-)summer period of 20 cases were very dry, 15 were notably dry, 17 were – on the Carpathian basin level – average, and four were wet. Thus, around 2/3 of the cases were related to dry or very dry conditions. Nevertheless, the negative influence of other weather extremes (e.g. hard winter, late frosts) as well as the impact of socio-economic processes also has to be considered, and these provide a significant bias while studying the relationship between dry conditions and harvest results. Moreover, there were also changes within the late medieval period that has to be considered: for example, the increase in documentation and the quantity of the available legal evidence (see e.g. Kiss 2019a), the growing population and export possibilities (e.g. grain) or the increasing cattle export and the need for fodder (i.e. increased importance of haylands).

A small group of cases can be related to controversies and purchasing Danube islands: as we could see before, in 1393–1394 the water level of the Danube was most probably quite low. Other interesting cases are related to island purchases: these cases lead us back to the late 13th–early 14th century. Danube islands were sold in 1262 and before early 1305, most probably in 1304 (Kiss, 2019a): according to both the OWDA and documentary evidence (see e.g. Rohr, 2007; Glaser, 2013), both years were particularly dry not only in the Carpathian Basin, but also in Western and West-Central Europe. Moreover, extreme low water-level conditions of the Danube were directly reported in Lower Austria in 1304 that fits rather well to potential low water level conditions of the Danube that made island areas (temporarily) larger, and increased the chances of the owner to sell the island for a better price.

A further group of frequently-documented events that had a higher likelihood of occurrence in dry (and windy) periods is fires. Although (unintentional) fires can also occur during hard winters and/or other cold and windy periods, and therefore reported major fire events cannot be automatically connected to a dry spell or drought, fire outbreaks have more chance to become particularly extensive and destructive under dry and/or windy than wet conditions. Moreover, during hot (and dry) periods the likelihood for the occurrence of convective events with thunders and lightning – often responsible for the start of major fire events – is also much higher (e.g. 1506: Eger; see Kiss, 2017). Significant years with many fires were, for example, reported in 1473; but charters also refer to fires in a number of cases in the 14th, 15th and early 16th centuries.

For example, fires were reported prior to 1305, May 1314, in 1317, before 1324, in 1332, 1354 and 1400 – in these years dry or very dry conditions were reconstructed by the OWDA (Cook et al., 2015). However, other years with known major fire events, for example 1338, 1342, 1350, 1351 or 1356, were not marked as dry in the OWDA catalogue (data: Kiss, 2016). Nevertheless, as most of the fires can be only dated prior to its mention to an unknown time, this dating uncertainty may limit the possibilities for a more accurate comparison. More clear relationships between dry conditions and fires were documented in the late 15th–

early 16th centuries when almost all reported great fires occurred in years when dry or very dry conditions were suggested by the OWDA. For example, dry or very dry (spring-)summer periods coincided with the years with major town/settlement fires in 1482, 1489, 1500, 1506, 1512, 1515, 1518 or 1525; even if, for example, the town fires of 1518 and 1524 mostly do not ‘fit’ this series with its average or wetter conditions (data: Kiss, 2019b).

Another important group of indirect indicators in the late-medieval period is the major local-regional Ottoman Turkish raids (not the military campaigns of the emperor) in Hungary and Slavonia. Prolonged dry periods with low water levels of major rivers, dry summer-early autumn periods and/or hard winters with steady frosts (with or without snow) and firmly frozen rivers greatly increased the likelihood of swift Turkish raids. Thus, even if, similar to fires, this indicator does not necessarily refer to dry conditions, dry conditions – just like in the 1517 case – made favourable conditions for the Turkish troops nearby the country borders for a devastating attack in (Northern) Slavonia or Southern Hungary. Years with swift devastating Turkish attacks, also mentioned in documentary evidence as dry were, for example, 1473, 1474 and 1479. Moreover, the OWDA suggests notably dry conditions or even drought in other years with known major Turkish raids, for example, in 1418 (see Bánlaky, 1928; Cook et al., 2015).

Food shortages and the mention of dearth or famine – as well as prolonged problems among traditionally pastoral communities – generally refer back to (multiannual) harvest problems, often, but not exclusively induced by drought. As for the pastoral communities, the problems of the Morlachs in Dalmatia were mentioned in relation with the great drought in the early 1360s and the grave poverty of Cumans and Iasonians in the early/mid-1470s and 1410s (see Kiss and Nikolić, 2015; Kiss 2017, and the present paper). Some of the reported significant food shortages such as, for example, 1312 (Kiss et al., 2016), coincided with very dry conditions in the OWDA for 1312 and also with Central European documentary evidence for 1311 and 1312 (Rohr, 2007; Cook et al., 2015; Kiss et al., 2016). Another case that refers to countrywide problems is 1381: in this year there was significant dearth (see Kiss et al., 2016). As there was also plague epidemic in the country, dearth might be also due to that; however, as based on the OWDA this year was very dry in the Carpathian Basin, another possibility is that, due to drought, the harvest was bad in this year. A further, thought-provoking example is the report from Csicsér (Čičarovce-Sk; see Fig. 1) in the north-eastern part of the Great Hungarian Plain about the grave poverty, starvation and even death of serfs in 1500; another year suggested as rather dry by the OWDA (Cook et al., 2015).

As we could see it on the example of 1517, apart from food shortages, large-scale shortage or lack of animal fodder could as well have disastrous consequences, in the form of mass loss of animals – especially when a hard winter followed the bad hay harvest caused by drought. On a local scale, probably similar problems were recorded in Temes County in May 1511, when during the hard winter of 1511 a significant shortage or lack of hay developed, and some serfs and landowners started illegally or even forcedly take their neighbours fodder (HNA DL 37883). As both (spring-)summer periods of 1509 and 1510 were rather dry according

to the OWDA, apart from the hard winter in Central Europe (see e.g. Brázdil et al., 2013; Glaser, 2013) that could be – even alone, in itself – responsible for the critical shortage of hay, previous weak hay harvest results, caused by drought, might have also been a contributing factor to the considerable shortage of fodder.

During prolonged food-supply problems there is a higher likelihood of social unrest as happened, for example, during the climatic anomaly of the early Spörer solar activity minimum (see Camenisch et al., 2016). It is also interesting that the great Peasant Revolt of 1514 (started in Transylvania already in 1513) was, according to the OWDA (Cook et al., 2015) and also to Central European documentary evidence for 1513 and 1514 (e.g. Rohr, 2007; Glaser, 2013; Brázdil et al., 2013), preceded by a rather severe multiannual (spring-)summer drought period (see also Kiss, 2019b).

Additionally, sometimes there are also interesting coincidences that might not have a key influence on the flow of events but probably still had some additional negative effects that made a crisis situation even graver. Although we found no direct mention of a drought in documentary evidence, an interesting example is the case of Trau/Trogir in 1420. As part of the (multiannual) Dalmatian war, in this year the town was besieged and cut off from all supply (see e.g. Bánlaky, 1928), which caused great famine and lack of water in the town, and finally forced town citizens to give up resistance and accept Venice as their natural lord (Fejér, 1844a). Coincidentally, based on the OWDA, the Dalmatian coastline and Trogir in specific had to endure drought in these years. In fact, the drought was the most severe in 1420 (Cook et al., 2015), which circumstance might have made water (and food) supply for Dalmatian towns, and also for Trogir, even more difficult than in average or wet periods. The year 1420 was outstanding warm in West and Central Europe also based on documentary evidence (see e.g. Brázdil and Kotyza, 1995).

Hunger in extensive areas of Dalmatia was similarly recorded in 1413, referring to 1412 (Mályusz, 1994) – based on the OWDA a year with rather dry conditions in the Croatian kingdoms (including Dalmatia) and most of Hungary. However, similar to 1420, war with Venice (and potentially also pestilence) might also have negative impacts in these areas, though in this year the lands of Dalmatia were less directly affected by the war than in 1420 (Bánlaky, 1928). Even further back in time, a potentially similar case was recorded in 1304, when great poverty was described in “Slavonia” (referring to any of the Croatian kingdoms) – one of the reasons of these grave problems might be political uncertainties (Kiss, 2016). Nonetheless, as suggested by the OWDA and also documentary evidence from other parts of Central and Western Europe (e.g. Alexandre, 1987; Brázdil and Kotyza, 1995) a possible reason could also be prolonged drought.

Another, rather indirect and uncertain but still thought-provoking case, this time in Hungary, is 1525. According to the Sperfogel chronicle, after many years of regular tax increase and the repeated devaluation of the currency, with reference to the (otherwise real) danger of a major Turkish attack, in 1525 the king decided to apply again the dangerous tool of money devaluation, which led

the country into great price increase and the lack of even basic goods purchased abroad (Wagner, 1774). And although no any mention of a drought is known from contemporary evidence, based on the OWDA there was significant drought in 1525 that could increase the negative consequences of the money devaluation and the possibly multiannual impacts of plague epidemics, hitting the country in 1522-1524 (see Kiss, 2019b).

As we could see in the present paper on the example of the 1370s, in certain cases the conditions of watermills, ditches (stagnant water bodies, fishponds/fisheries, meadows) might be applied as indirect indicators of a dry spell. Additionally, further potential, indirect indicators might be worth to test in future. In England, for example, even the mention of dried up trees in contemporary administrative sources in certain years might be an indicator of drought (see e.g. Pribyl, 2017).

OWDA droughts – with no documentary evidence?

Although regarding many of the years, highlighted by the tree-ring based OWDA hydroclimate reconstruction, at least indirect evidence is available, some markedly great drought years in the OWDA reconstruction up to now has no any connected, direct or indirect, late medieval documentation in the Carpathian Basin.

Based on the OWDA, in the Carpathian Basin the cumulative (extrapolated) PDSI values were under (or around) -1 in 1300, 1303, 1306, 1311, 1314, (1317), 1320, 1322-1324, 1326, (1328), 1334, 1335, 1354, 1355, 1357, 1358, 1365, (1367), 1377, 1381, 1385 and 1403-1406, 1412, 1417, 1419, 1422, 1423, 1427, 1431, 1433, 1443, 1444, 1500, 1503, 1506, 1507, 1513, 1514, 1518 in late medieval times. This value was (around or) under -2 in (1312), (1323), 1325, 1332, 1360, (1362), 1384, 1420, 1421, 1426, 1439, 1440, 1473, 1479, 1480, 1483, 1484, 1504, 1512, 1516, 1519, (1520), 1525. In two cases, in 1333 and 1517, the PDSI value was under -3, and in one case in late medieval times this index value was under -5, in 1361 (data: Tree Ring Drought Atlas Portal).

However, we have to add that these values refer to the entire Carpathian Basin, and within this large region, there could be great regional differences in drought intensity within the same year. For example, in case of a great drought in the eastern and central parts of the Carpathian Basin, it was rather possible that the drought did not affect the western parts of the Basin, and in this case the average PDSI index might not show any extreme on the level of the entire Carpathian Basin, even if clearly there was a significant drought in that year. A potential example for such a case is 1507 (see Kiss, 2019c).

Out of the years with under -3 PDSI values, we have not yet found any documentary-based reference for 1333, but sources do refer to 1361 and 1517 (Kiss, 2017; and in the present paper). Direct or indirect evidence is also available for the years with PDSI values under -2, in 1360, 1362, 1420, 1426, 1439-1440, 1473, 1479-1480, and probably for 1483 and 1504, but some kind of (even if very indirect) information can as well be connected to most of the years with PDSI values under -1 (see examples in the present paper), even if the causal relationship in most cases cannot be proved with certainty.

CONCLUSIONS

In the present paper potential dry spells, mainly available in indirect evidence, as well as uncertain and contradictory cases are discussed and compared to the tree-ring based (spring-)summer hydroclimate reconstruction of the OWDA. Direct and indirect evidence refers to dry spells or even a potential drought in the 1370s, while a contradictory, mixed dry and probably very rainy and then again dry periods are discussed in the 1410s, and a potential multiannual dry spell or drought in the 1420s. Rather clearly drought-related information comes from the year of the Reformation, 1517, with indirect reference to 1516.

Furthermore, groups of (potential) indirect evidence, presented in medieval legal-administrative (mainly charter) documentation were defined. The presence and more frequent occurrence of problem groups in certain years or periods may help us to identify more dry spells or droughts without direct reference in contemporary documentation.

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